OPPORTUNITIES AND APPROACHES FOR DOUBLING THE STRUCTURAL EFFICIENCY OF METALLIC MATERIALS

NATO Advanced Research Workshop

Metallic Materials with High Structural Efficiency

9 September 2003

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Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE **09 SEP 2003**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Opportunities And Approaches For Doubling The Structural Efficiency Of Metallic Materials**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air Force Research Laboratory, USA**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S)
		11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES **See also ADM001672., The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**62**	

Standard Form 298 (Rev. 8-98)
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OUTLINE

HIGH STRUCTURAL EFFICIENCY

—What is it, and why is it important?

STRUCTURAL EFFICIENCY OF METALLIC MATERIALS

CANDIDATE TECHNOLOGIES

SUMMARY

HIGH STRUCTURAL EFFICIENCY

Stiffness and strength are primary design factors in every aerospace structure

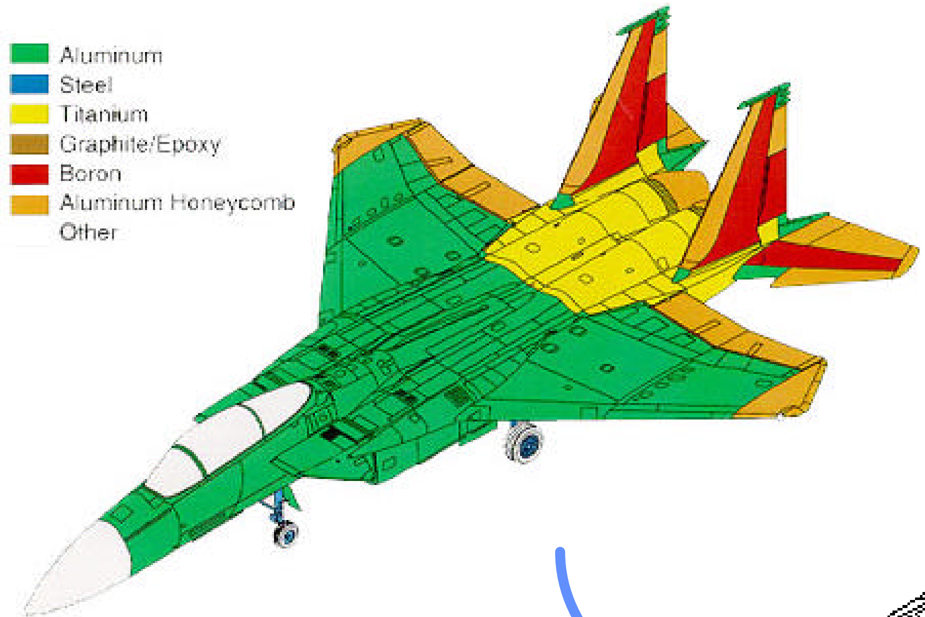
– controls size (mass) and spacing (number) of structural members
– reduces deflections, controls instabilities
– fatigue response often scales with stiffness
– stiffness defines vibrational frequencies

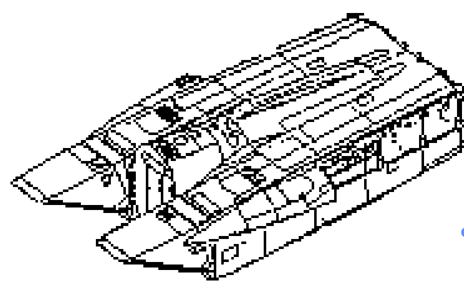
Higher specific properties provide equivalent structural response at reduced mass– *higher structural efficiency*

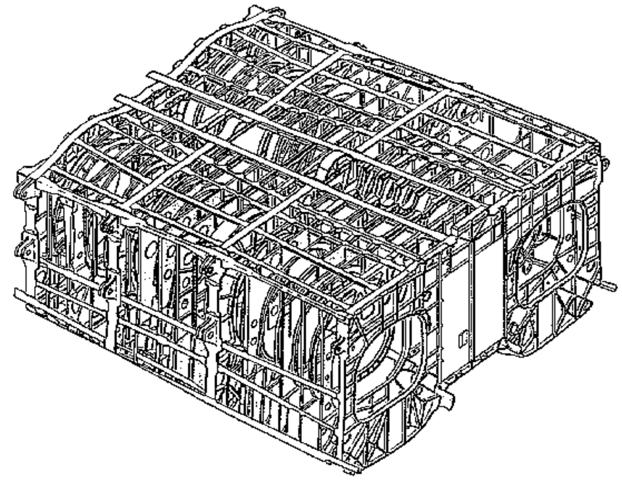
– doubling specific properties decreases weight by ¡ 50% *without redesign*
  - ✓ improved performance for dynamic parts and systems
  - ✓ enabling requirement for many advanced aerospace systems
– enables more efficient design, such as unitized construction
– fewer parts provides significantly improved affordability

Isotropy is required to provide pervasive technology impact

AIRFRAME CONSTRUCTION







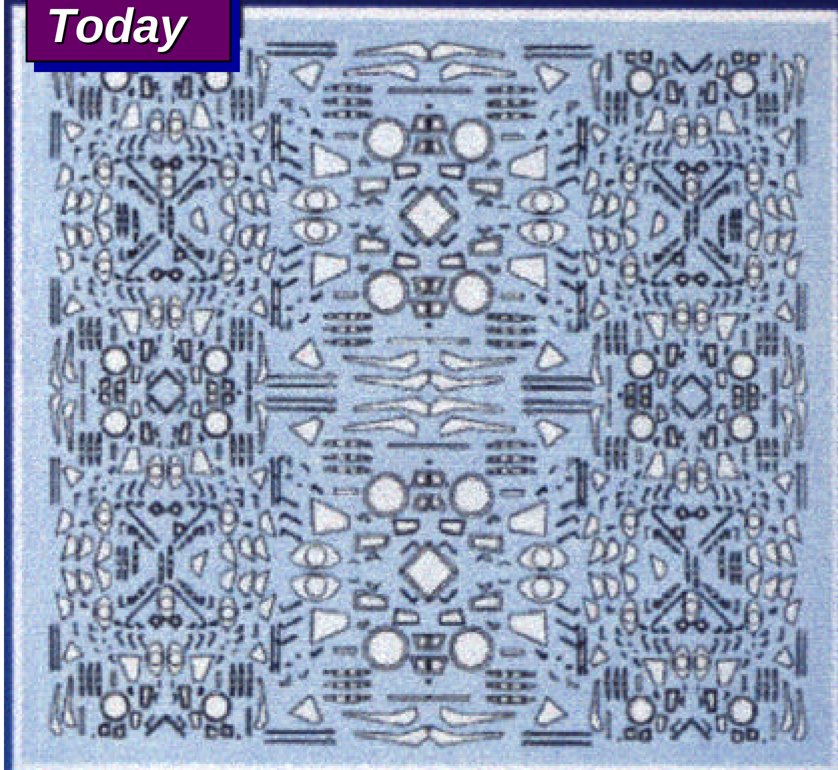
Skin/stringer construction is inefficient

– low E/ρ requires close spacing of support structure
– joints do not transfer loads efficiently
– many simple detail parts require expensive assembly operations

Composites Affordability Initiative

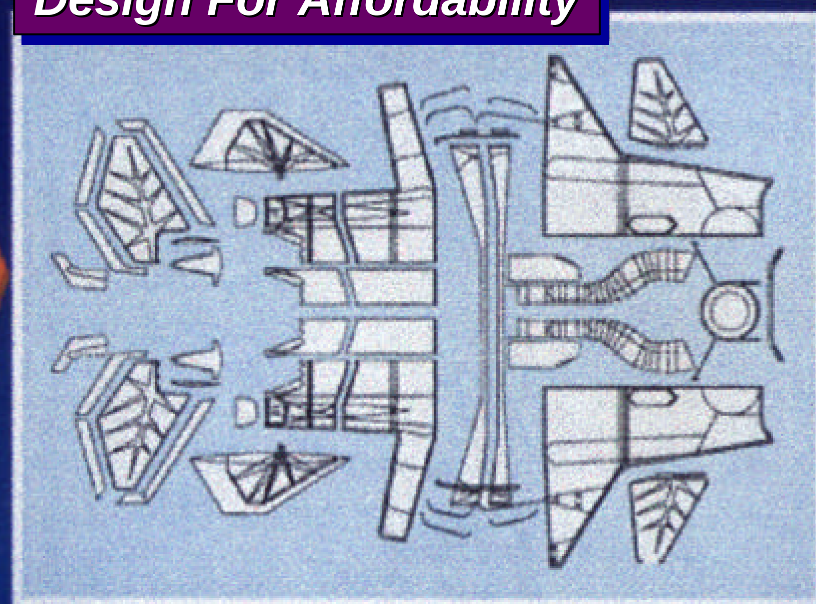
OUR VISION

Today



- 11,000 Metal Components
- 600 Composite Components
- 135,000 Fasteners

Design For Affordability

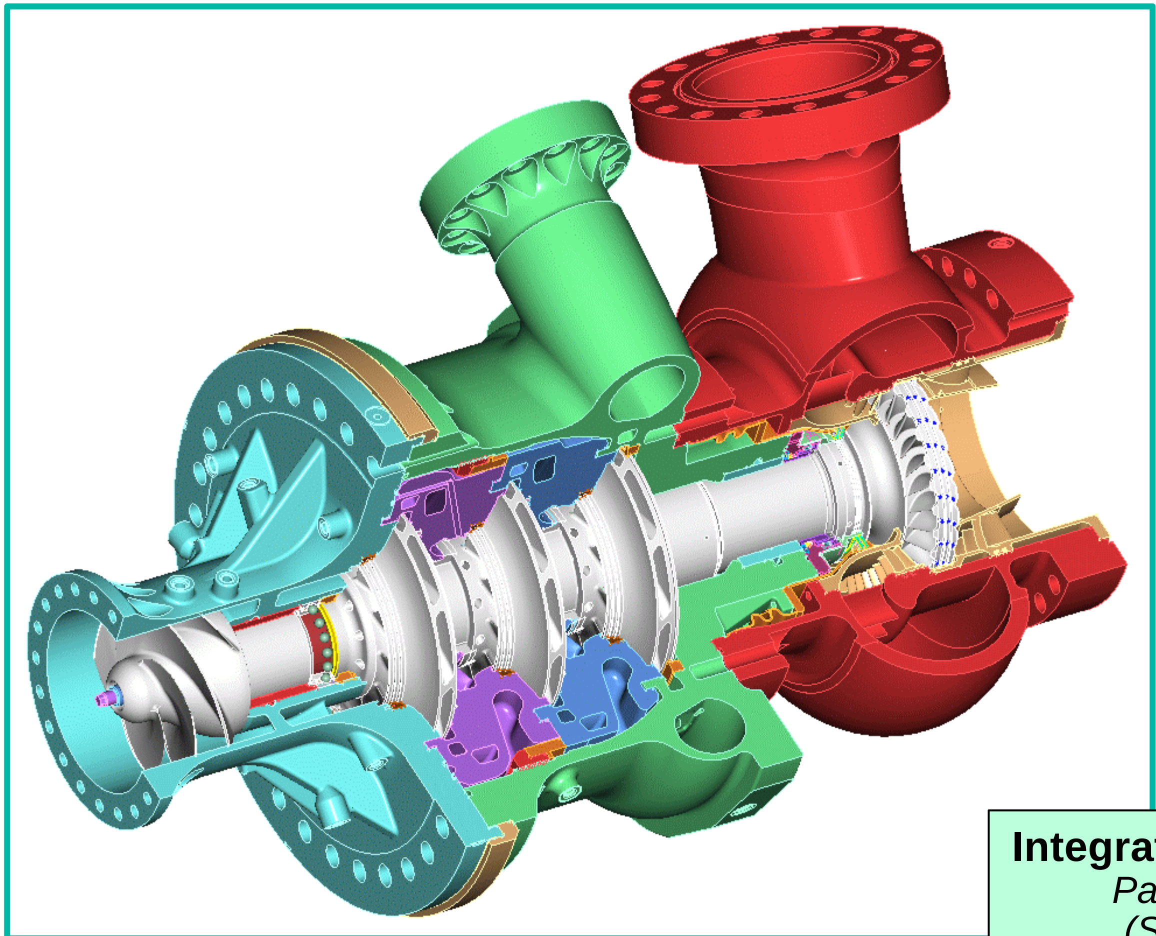


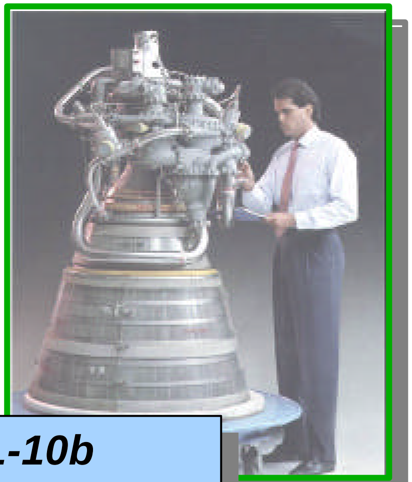
- 450 Metal Components
- 200 Composite Components
- 6,000 Fasteners

- *Reduce Part Count*
- *Improve Producibility*
- *Dramatically Reduce Assembly Costs*

BOEING LOCKHEED MARTIN NORTHROP GRUMMAN

Advanced LH_2 Turbopump
Advanced Metals Enable Simplified Design



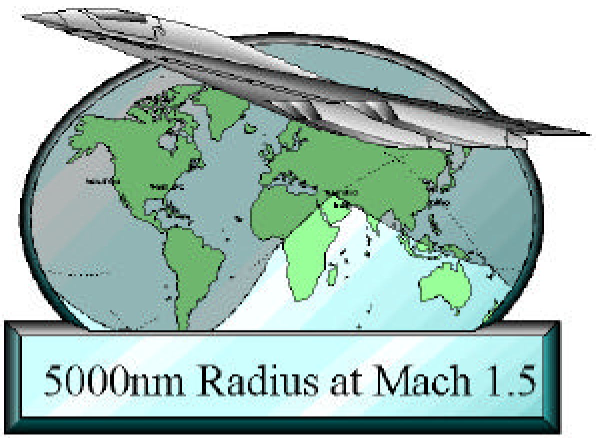


_RL-10b_
Rocket Engine

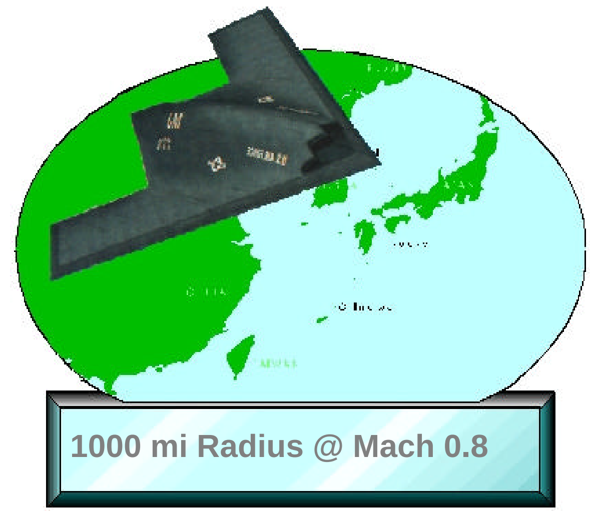
Integrated Powerhead Design
Part Count = 524 pieces
(SSME = 1433 pieces)

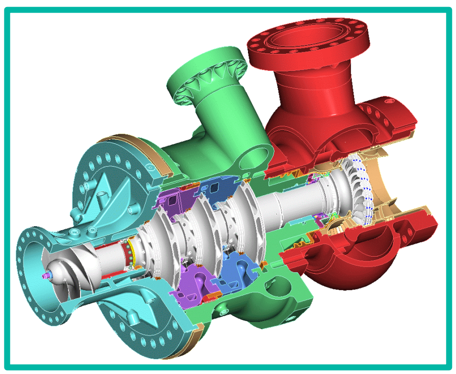
Sophisticated manufacturing and design and improved material properties enable reduced part count and cost

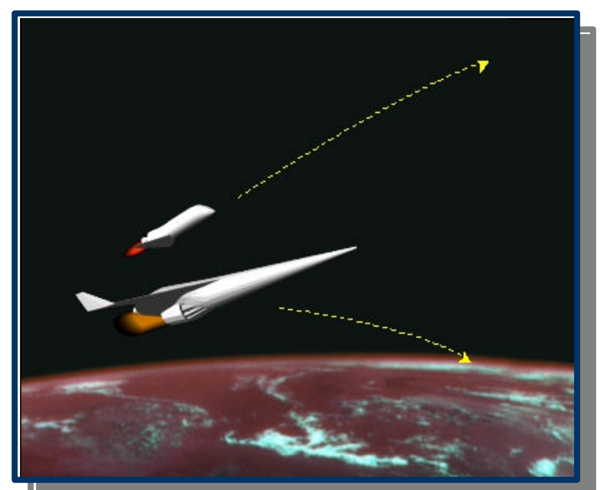
A Full Spectrum of Dreams… and Demands for Better Materials



- Global Reach Aircraft
- Multi-role Unmanned Air Vehicle (UAV)
- SensorCraft UAV
- Hypersonic (Mach 8-10) Aircraft
- Reusable Space Lift
- Single Stage to Orbit
- Advanced Liquid Rocket Engines
- Hybrid Propulsion







OUTLINE

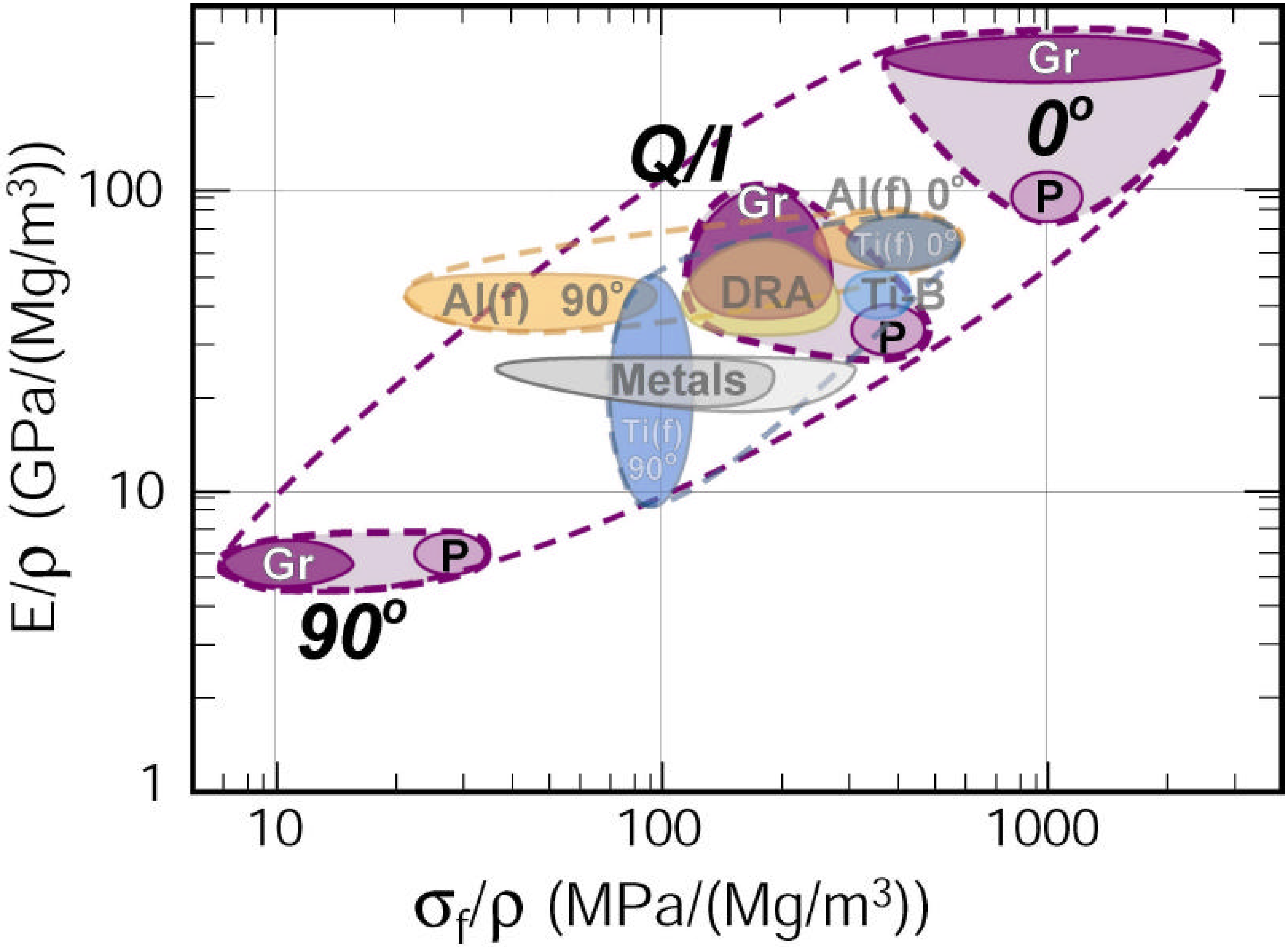
HIGH STRUCTURAL EFFICIENCY

STRUCTURAL EFFICIENCY OF METALLIC MATERIALS

CANDIDATE TECHNOLOGIES

SUMMARY

SPECIFIC PROPERTIES

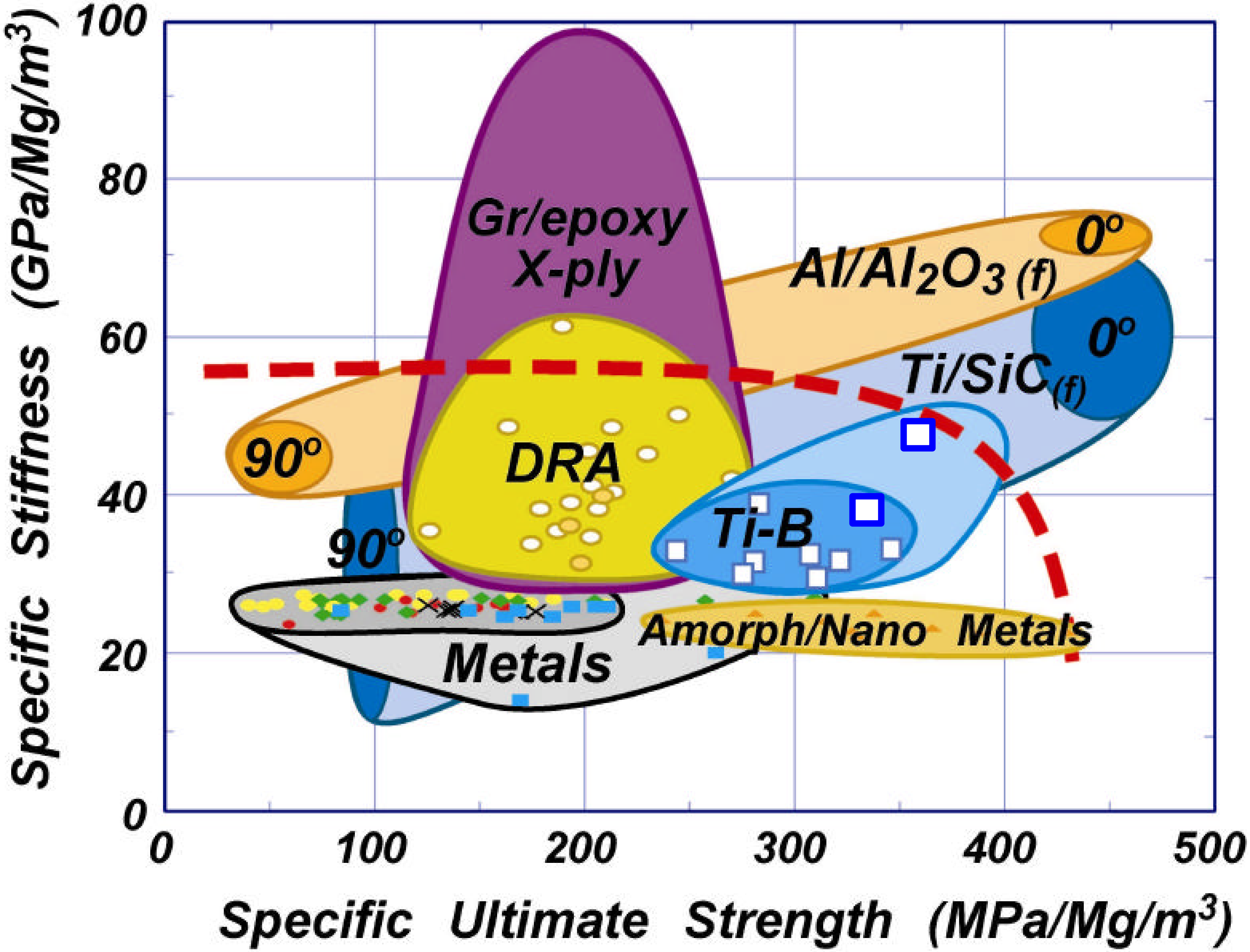


METALS vs. ORGANICS

- **Metals will not compete with OMC's when ambient temperature structural efficiency in one direction is the only consideration**
  - primary advantages of metallic materials include elevated temperature capabilities and isotropic properties
- **Aerospace applications often require secondary characteristics which enable the material to achieve the primary function**
  - compatibility with aggressive environments (hot oxidizing and corrosive gases, wet corrosion, hydraulic fluid, jet fuel, cryogens, AO, UV, ionizing radiation . . .)
  - fatigue resistance
  - high bearing loads for fasteners, assembly
  - affordability, supportability . . .

Metals typically excel in secondary characteristics required for structural applications

STRUCTURAL PROPERTIES



HIGH STRUCTURAL EFFICIENCY

- **DRA offers very good specific stiffness, with modest improvement in specific strength**
  - ability to implement highest specific stiffness limited by inadequate fracture properties
  - higher specific strength can be obtained by improved matrices or by selective fiber reinforcement
- **Amorphous metals offer exceptional specific strength, but marginal specific stiffness and fracture properties**
- **Boron-modified Ti (Ti-B) offers significant improvements in both specific strength and stiffness**
- **Continuously reinforced MMCs offer very good specific strength and stiffness along the fiber direction, but poor transverse properties and poor ability to produce complex shapes**
- **Nanocrystalline metals offer approach for achieving high strength and good fracture properties**

OUTLINE

- HIGH STRUCTURAL EFFICIENCY
- STRUCTURAL EFFICIENCY OF METALLIC MATERIALS
- **CANDIDATE TECHNOLOGIES**
  - **MMCs**
  - Advanced Al
  - Ti-B Alloys
  - Metallic Glasses
- SUMMARY

MMC WORLD MARKETS[@]

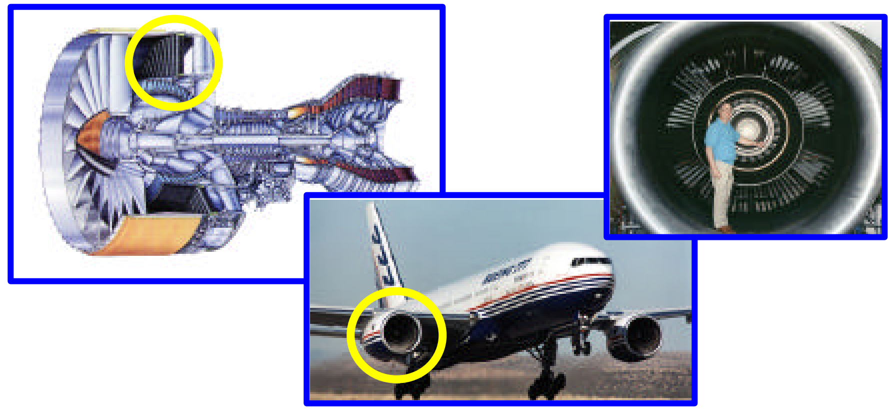
- **MMC's represented a business volume of >2500 metric tons in 1999, valued at >$100M**
  - **Ground Transportation represents largest market by volume (62%), but Thermal Management represents largest market by value (66%)**
  - **Aerospace represents 5% by volume (~140 metric tons), 14% by value (~$15M)**
  - **Other major markets include industrial and recreational**
- **Al MMC's represent the largest market volume at 69%, while refractory MMC's (Cu/W, Cu/Mo) represent 25%**
  - **Other MMC systems include Ni, Ti, Be, Fe**
- **Liquid metal processing represents about 2/3 of the market by volume, and about 1/4 the market by value**
  - **existing aerospace applications use only MMC produced by solid state processes**

[@] **M. Rittner, *MMC's in the 21st Century: Markets and Opportunities*, BCC, Inc., 2000**

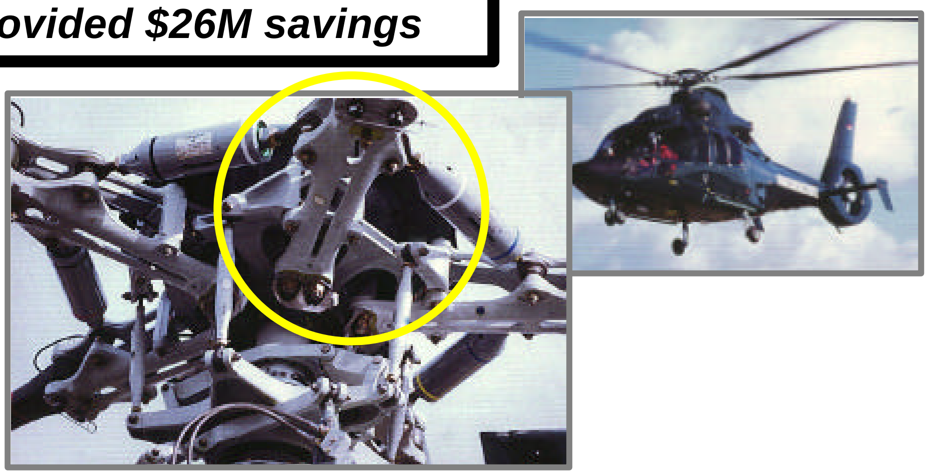
Discontinuously-Reinforced Al

High Specific Properties Offer Performance and Affordability

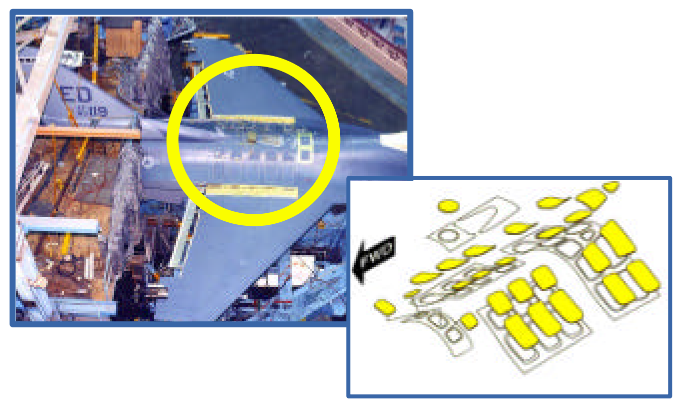
F-16 DRA Ventral Fin has provided $26M savings



DRA has replaced gr/epoxy fan exit guide vanes in PW 4XXX engines



DRA has replaced Ti in flight-critical application on N4, EC-120 Helicopters



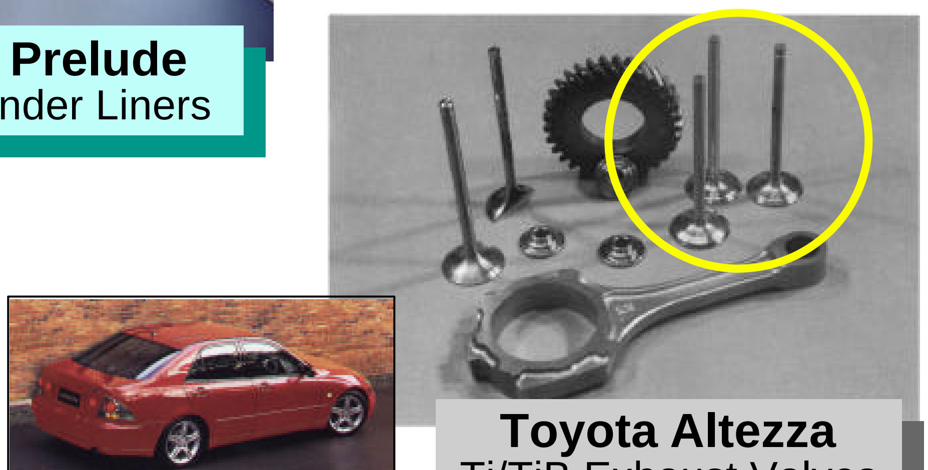
DRA fuel access doors have reduced fuselage cracking in F-16

Discontinuously-Reinforced Al

High Specific Properties Offer Performance and Affordability

Honda Prelude
DRA Cylinder Liners

Plymouth Prowler
DRA Brake Rotors

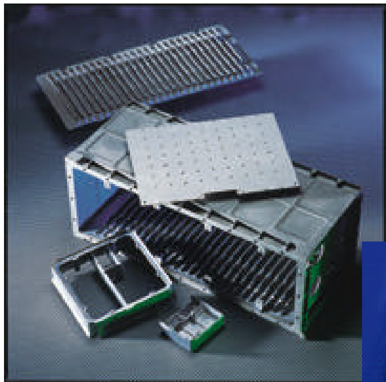


Toyota Altezza
Ti/TiB Exhaust Valves

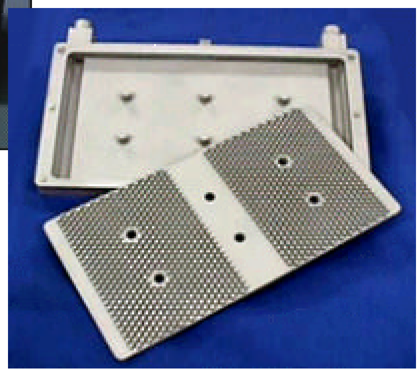
Chevy Corvette
DRA Driveshaft

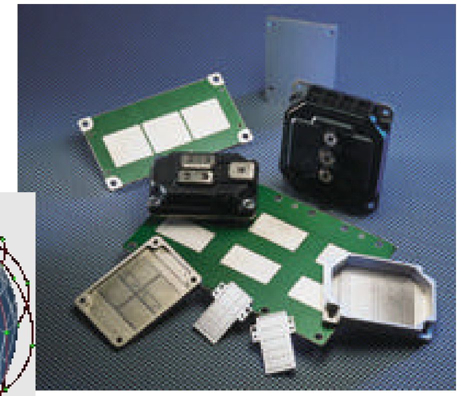
Discontinuously-Reinforced Al

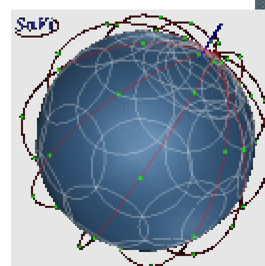
High Specific Properties Offer Performance and Affordability



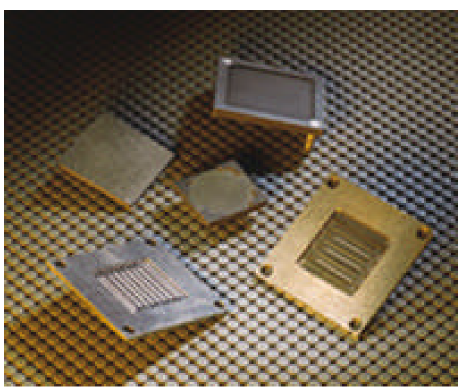
DRA active cooling systems, chassis, and enclosures provide dramatic improvements in weight, performance, and cost







DRA has replaced Fe/Ni, Cu/Mo and Cu/W for chip carriers and microwave devices



QuickTime™ and a
Planar RGB decompressor
are needed to see this picture.

DRA is used for power semiconductor bases in GEO comsats, cell phone base stations

DISCONTINUOUSLY REINFORCED MMC CHARACTERISTICS

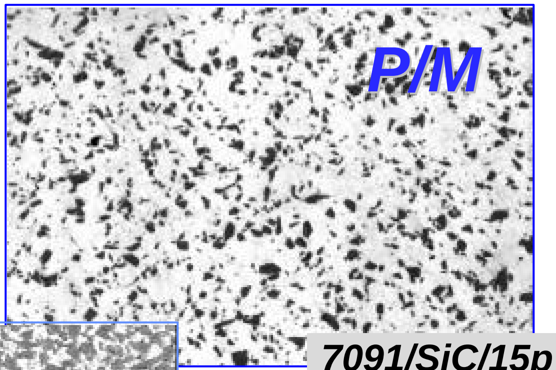
Composition
- ✓Al, Fe, Cu, Ti . . . matrix with 10-70% SiC, Al_2O_3, B_4C, TiC . . . reinforcements

Microstructure
- ✓extensive range of control for matrix microstructure and particulate distribution

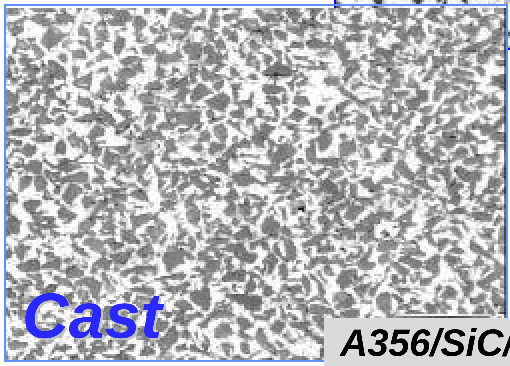
Processing
- ✓wrought, cast, P/M techniques
- ✓established and affordable for most primary and secondary processes
- ✓utilizes existing infrastructure

Properties
- ✓high specific stiffness, strength
- ✓excellent fatigue– 270 MPa @ 10^7 cycles
  v. 155-180 MPa for 2024-T4 and 7075-T6
- ✓isotropic properties
- ✓metallic behavior
- ✓tailorable stiffness, CTE

Applications
- ✓structural
- ✓thermal
- ✓wear
- ✓electrical



7091/SiC/15p



A356/SiC/60p

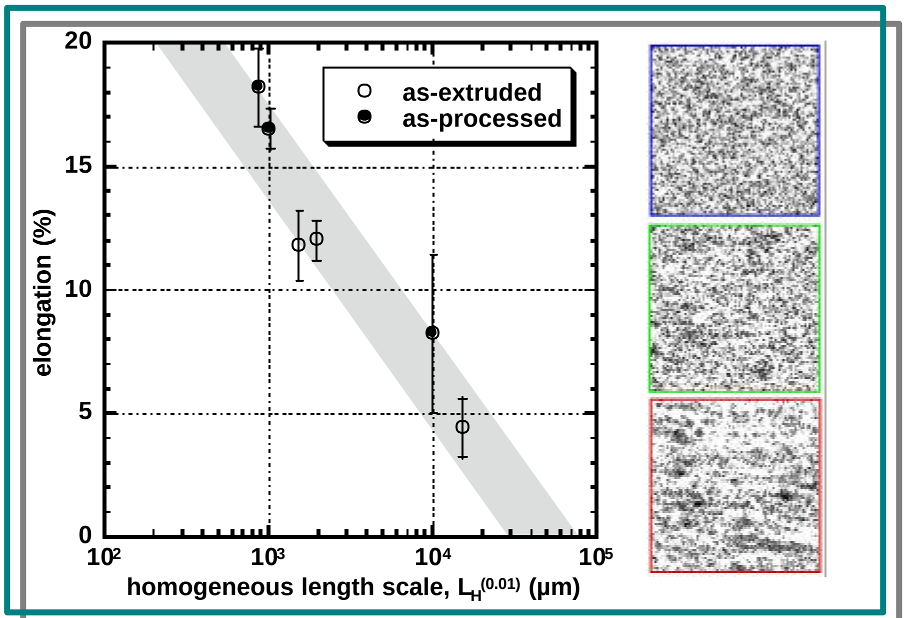
DISCONTINUOUSLY-REINFORCED MMC'S (DRX)

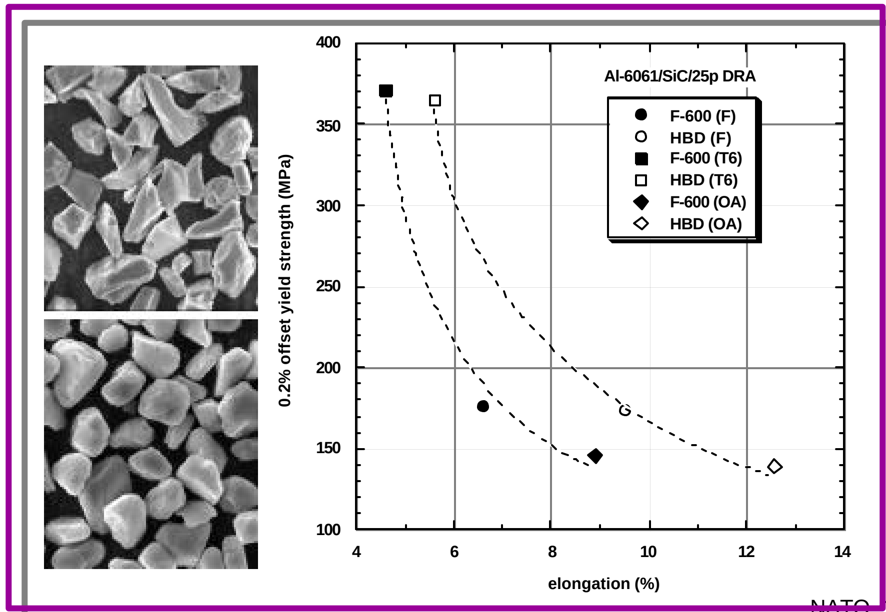
Improved structural efficiency of DRX can be achieved with a higher volume fraction of reinforcements

- for DRA, reinforcement volume fraction $f > 0.20$ produces inadequate ductility and toughness for fracture-critical structural applications

Influence of morphology, volume fraction and distribution of reinforcements must be established

- scientific basis for quantifying distribution now being established
- positive influence of particle morphology has been established



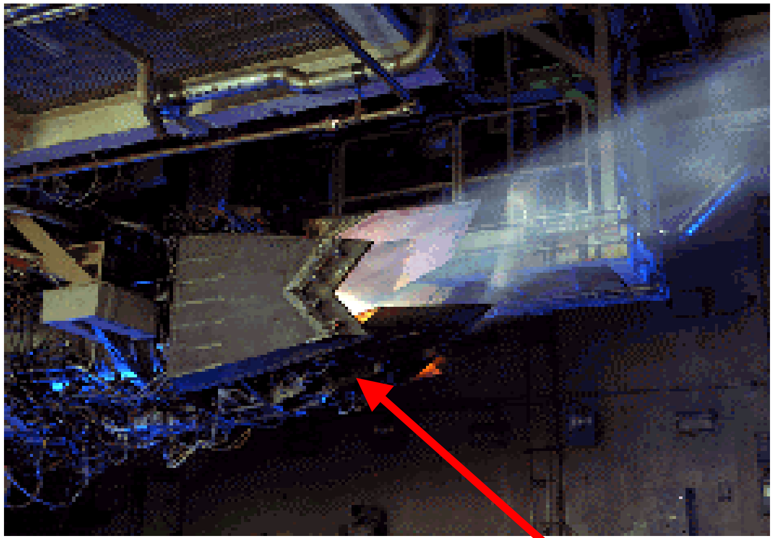


FMW COMPOSITE SYSTEMS, INC.

Composite Design & Manufacturing

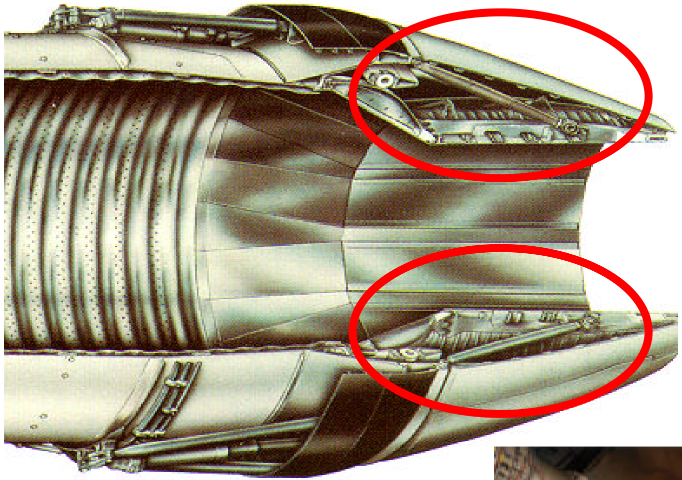
TMCs Have Achieved Production Status

F119

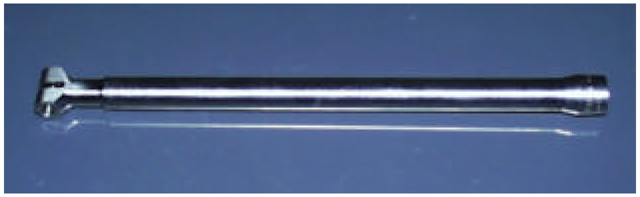


FMW
Actuator
Piston Rod

F110

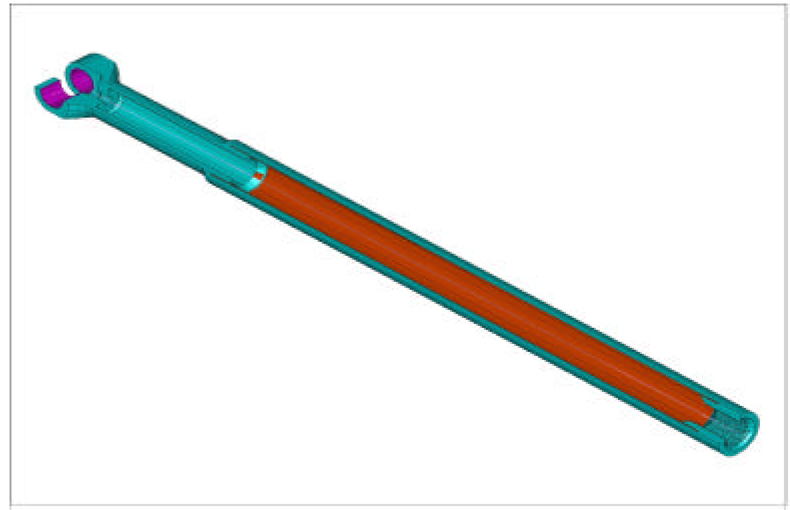


FMW
Compression Links



FMW COMPOSITE SYSTEMS, INC.

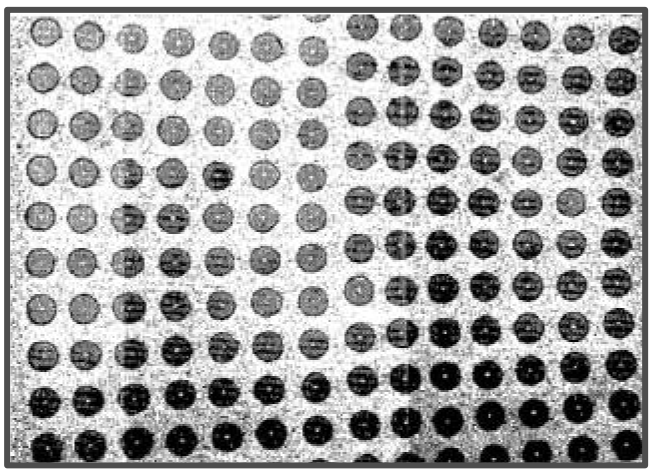
Composite Design & Manufacturing

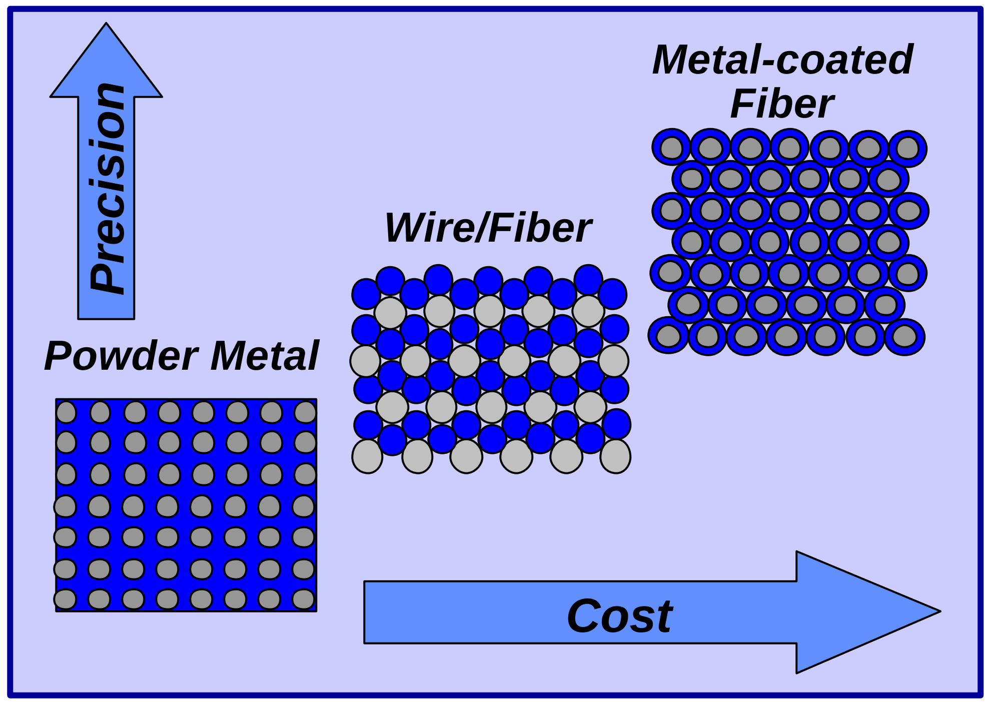


Progress toward affordable TMC products has been achieved in uni-directional selectively reinforced components.

A dramatic reduction in TMC component cost has lead to the achievement of production status.

Success has initiated a developing market for this type of component.





FMW COMPOSITE SYSTEMS, INC.

Composite Design & Manufacturing

Titanium Matrix Composites Ti-6Al-4V/SiC

Ultimate Tensile Strength (Longitudinal	*Steel Strength/Stiffness*	1690 MPa (245 ksi)
Young's Modulus (Longitudinal)		200 GPa (29 Msi)
Ultimate Tensile Strength (Transverse)	*Limiting Property*	400 MPa (58 ksi)
Young's Modulus (Transverse)		145 GPa (21 Msi)
Low Cycle Fatigue, Longitudinal [120 ksi (830 MPa), R=0.1, 3Hz]		>500,000 cycles
Low Cycle Fatigue, Transverse [27.5 ksi (190 MPa), R=0.1, 3Hz]		>500,000 cycles
High Cycle Fatigue, Longitudinal [77 ksi (530 MPa), R=0.1, 30Hz]		> 10^7 cycles
High Cycle Fatigue, Transverse [13 ksi (89.6 MPa), R=0.1, 30 Hz]		> 10^7 cycles
Compression Strength	*> 2X Steel*	>4480 MPa (>650 ksi)
Density	*Half Steel Density*	3.93 gm/cm^3 (0.142 lb/in^3)
CTE		5.9 x 10^{-6}/°C (3.3x10^{-6}/°F)

FMW COMPOSITE SYSTEMS, INC.

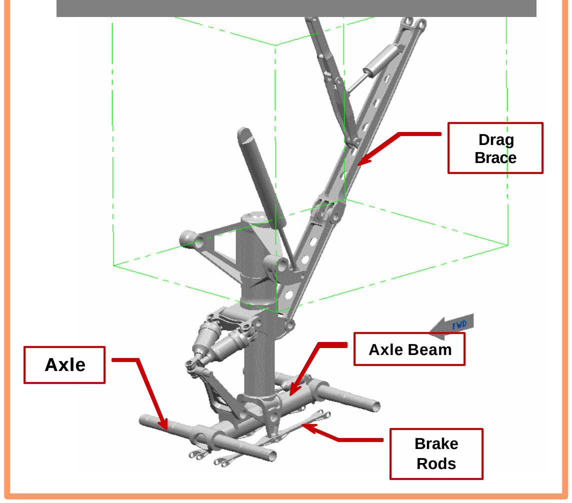
Composite Design & Manufacturing

Next Major Challenge For TMC Market Expansion

Development efforts are underway to address transverse property improvement.

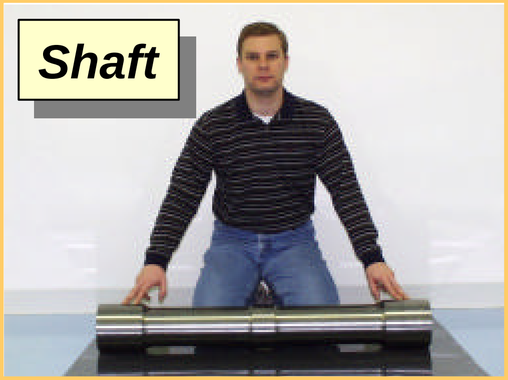
- SiC fiber coating strength
- Boron modified titanium matrix alloys (Ti-B) for continuously reinforced Ti-MMCs provides unique opportunities for hybrid composites

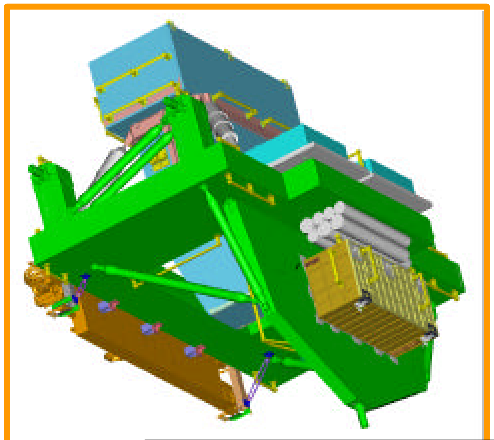
Landing Gear Assy



Aileron Link

Shaft





Shuttle Palate

FIBER-REINFORCED MMC'S

Prospective matrices include Ti, Al, Cu, Ni . . .

- applications include structural, thermal, electrical . . .
  - aero structures, cryo tankage, orbital spacecraft, liquid rocket propulsion, gun barrels, directed heat transfer . . .
- multifunctionality for structural/thermal or structural/electrical
- shape memory alloys (SMA) provide sensor/actuator functions

Scientific foundation and practical techniques to tailor interface properties not yet known

- control composition and structure of C coatings for SiC fibers
- predictive capability for interface bond required
- common methods to quantify interface properties are inadequate

Advanced processing is essential

- selective reinforcement
- hybrid composites

Design concepts require investment

- selective reinforcement concept well-known, but not yet mastered
- cross-ply architectures not yet established for MMC's
- must be able to understand and control CTE mismatch and residual strains

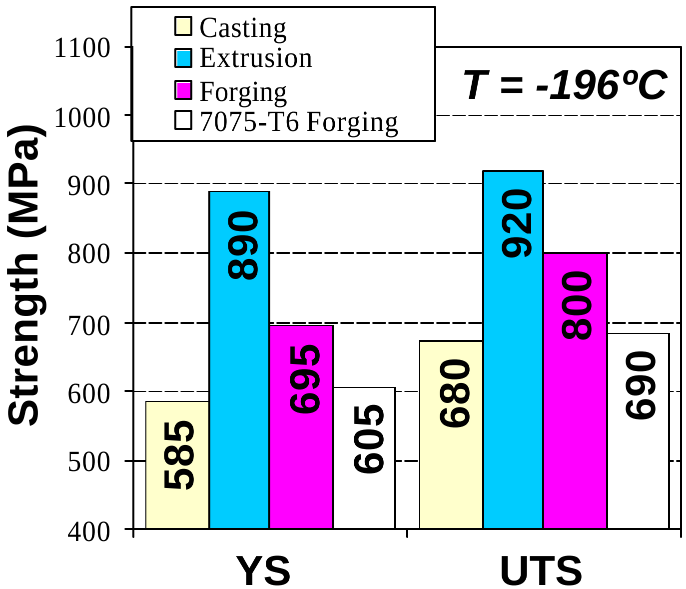
OUTLINE

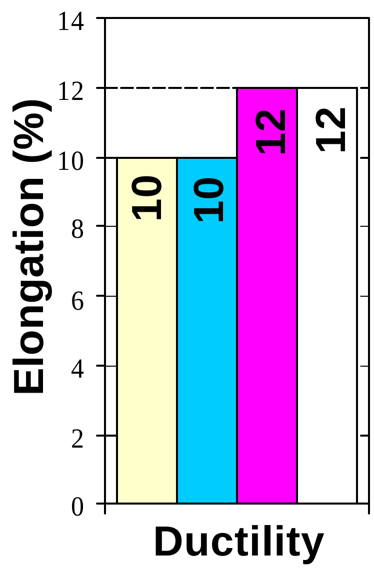
- HIGH STRUCTURAL EFFICIENCY
- STRUCTURAL EFFICIENCY OF METALLIC MATERIALS
- CANDIDATE TECHNOLOGIES
  - MMCs
  - Advanced Al
  - Ti-B Alloys
  - Metallic Glasses
- SUMMARY

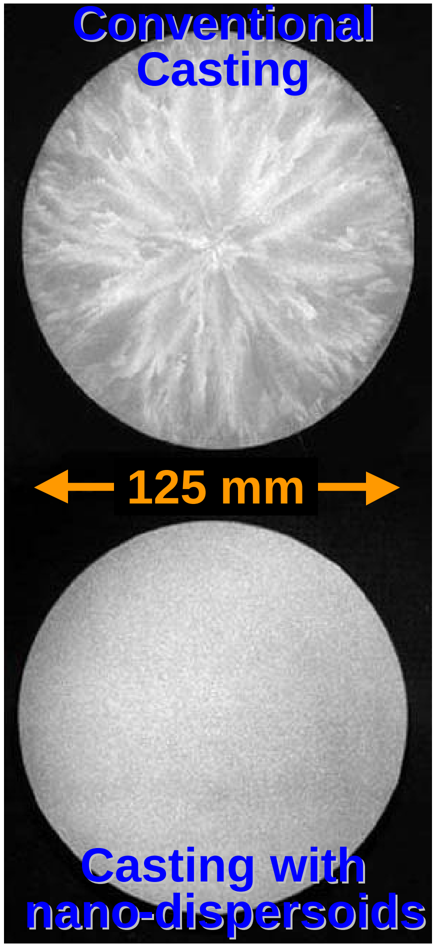
SUPER-HIGH STRENGTH Al
Dr. O.N. Senkov, UES Inc.

Collaborative effort is developing a new class of age-hardenable Al with dramatic increase in structural properties

– both metastable precipitates and thermodynamically stable dispersoids are uniformly dispersed in the microstructure
– dispersoids are 5-10nm in diameter and provide strength and microstructural control
– strength increases of over 40% are achieved with excellent ductility
– material is cast and wrought with good affordability
– in-house effort funded through a Phase II SBIR



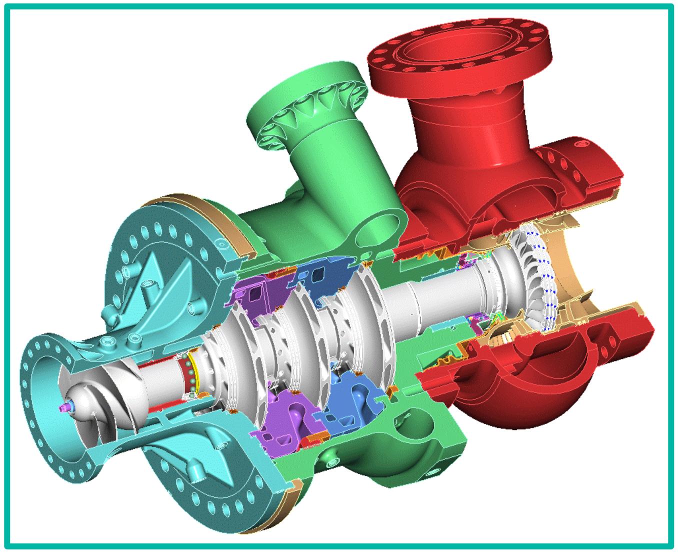




SUPER-HIGH STRENGTH Al
Transition Opportunities

Transition opportunities for super-high strength Al alloy technology are being established

- funded collaboration is underway with Boeing/Rocketdyne for advanced LH_2 turbopump impeller, rotor and housing
  - *funded by AFRL/PR (Edwards AFB) through UES, Inc. (Dr. O. Senkov, PI)*
- selected as only structural metal technology for recent Missile Defense Agency (MDA) call for topics
- discussions have been initiated with Metals Affordability Initiative (MAI) based on dramatic potential for cost reduction of high performance Al alloys
  - *wrought strength can be achieved in a cast product*



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  - MMCs
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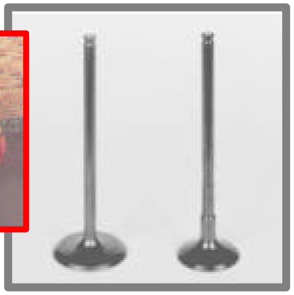
- SUMMARY

HISTORY OF Ti-B TECHNOLOGY

Early work in aeropropulsion industry

– Rolls-Royce



Independent effort at Dynamet, Inc.

– sinter and HIP powder metallurgy process
– produced commercially for small parts

NASA/Boeing effort on High Speed Civil Transport

– material iteration, process development, mechanical properties
– feasibility of large extruded parts established

Focused effort at Toyota has developed and transitioned Ti-B alloys for automotive intake and exhaust valves

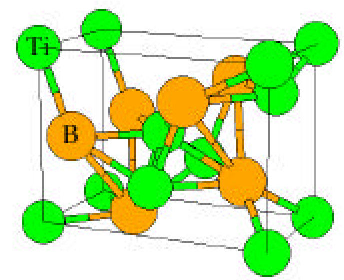
– lighter valves enable reduced spring mass, lower cycle losses
– over 500,000 parts manufactured by 2000

Ti-B is an established technology in automotive and commercial sectors, but requires development for aerospace applications

Ti-B COMPOSITIONS

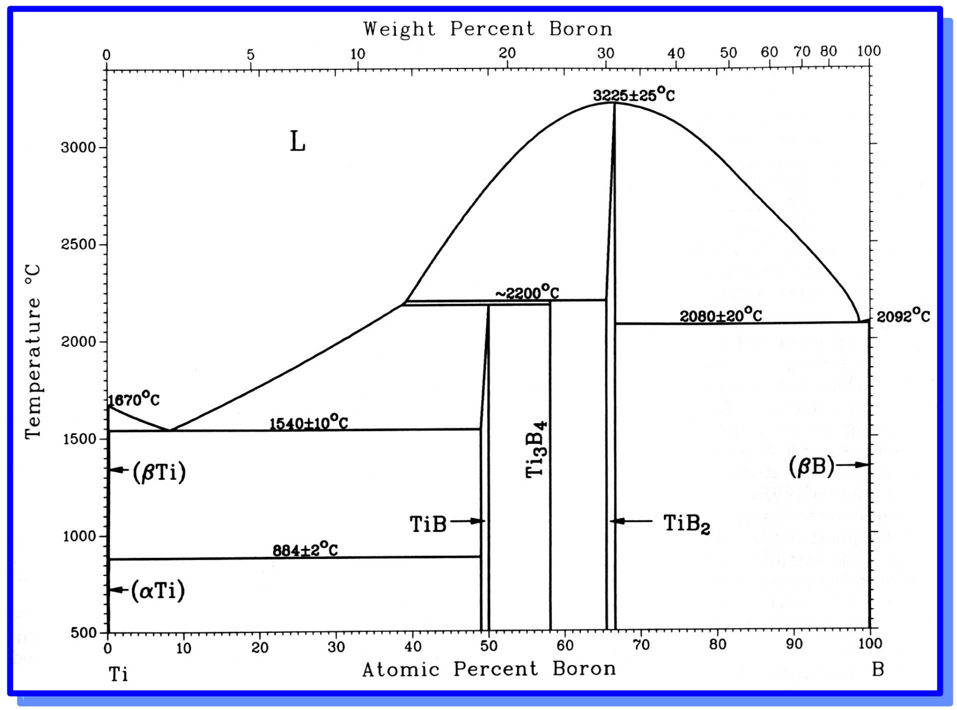
Alloy

- ✓B is essentially insoluble and does not embrittle Ti alloys
- ✓typically conventional $\alpha+\beta$, but may be near-α, β or orthorhombic
- ✓fine grained microstructure produced and stabilized by TiB



Intermetallic

- ✓volume fraction typically ~10%, but may be as high as 40%
- ✓TiB is formed *in situ*
- ✓TiB is chemically and thermally compatible with Ti alloys
- ✓TiB intermetallic is very strong and stiff (~480 GPa)
- ✓typically whisker-shaped with aspect ratio of 5-20
- ✓size depends upon processing



Ti-B PROCESSING

Cast

✓eutectic reaction provides castability, affordable near net shape possibilities

→*TiB intermetallic refines cast grain size*

→*limits TiB volume fractions to ~10%*

P/M

✓**prealloyed** powder processing provides fine TiB at cost comparable to conventional Ti P/M

→*limits TiB volume fractions to ~10%*

✓**blended elemental** powder approach provides higher V_f at higher cost

✓compatible with advanced materials and processes

→*continuously reinforced Ti-MMCs*

→*laser additive manufacturing*

Wrought

✓full range of primary and secondary techniques are feasible

→*extrusion, forging established for automotive applications with low B additions*

✓alignment of whiskers provides opportunity to tailor properties, but must be controlled

Ti-B MICROSTRUCTURES

Alloy

✓equiaxed fine grained alpha microstructure stabilized by TiB intermetallics

Intermetallic

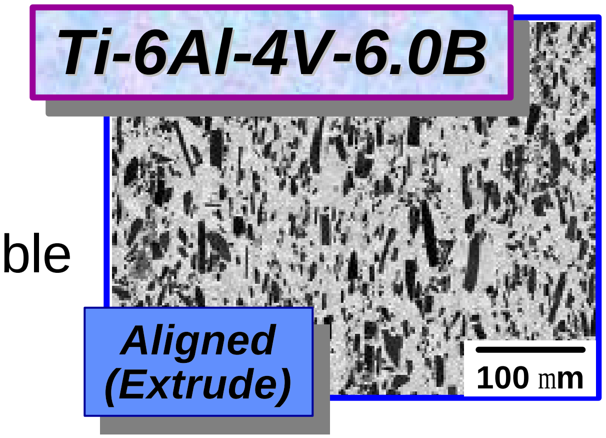
✓typical TiB morphology is whisker with *l/d* ~10:1

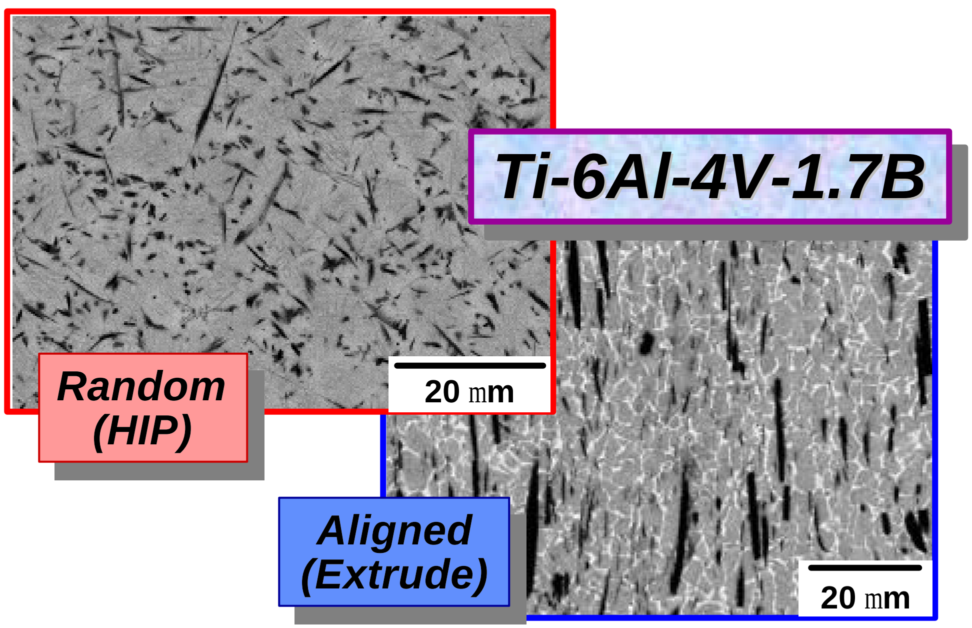
→*Width: ~1-5 μm and ~100 nm*

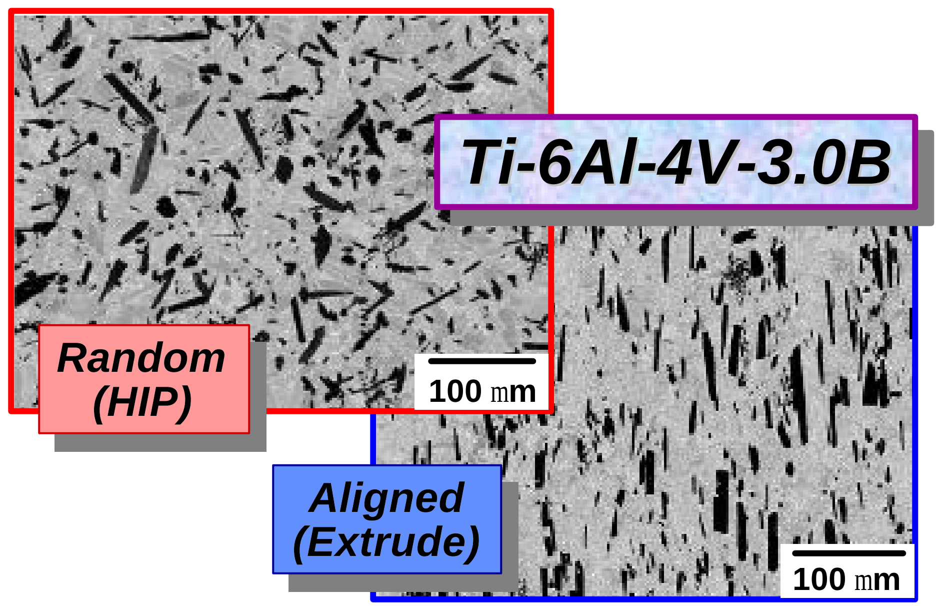
✓control of orientation and TiB volume fraction possible

→*aligned or random orientations possible*

→*volume fractions up to 40% are practical*



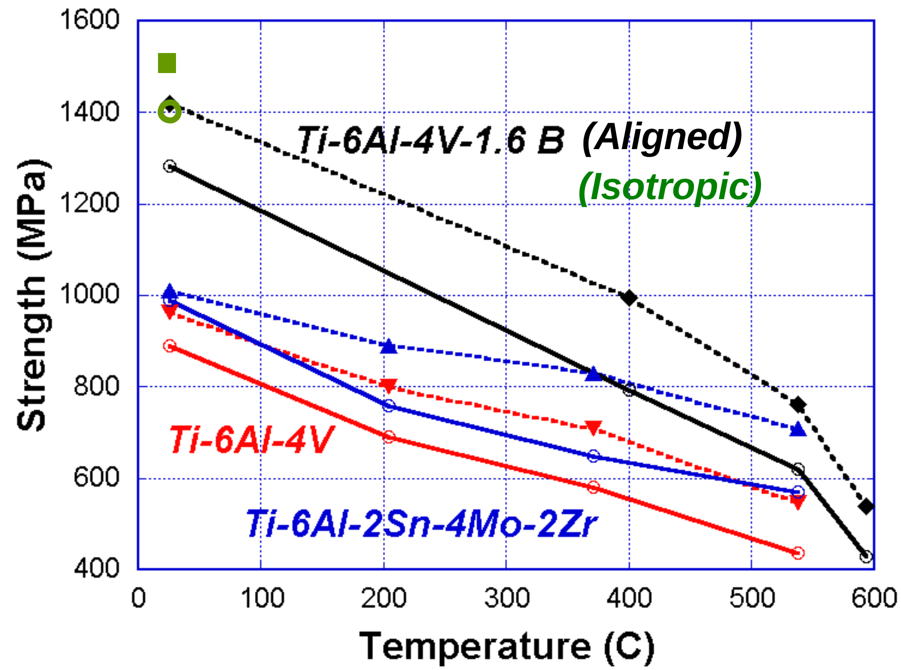




Ti-B MECHANICAL PROPERTIES

Structural and Functional

✓exceptional specific stiffness, strength
✓widely tailorable properties
✓isotropic or anisotropic properties
  → *alignment of TiB whiskers (1D) provides fiber-like properties*
  → *randomly oriented whiskers (3D) provides isotropic properties*
✓cost comparable to conventional Ti alloys
✓metallic behavior (supportable)

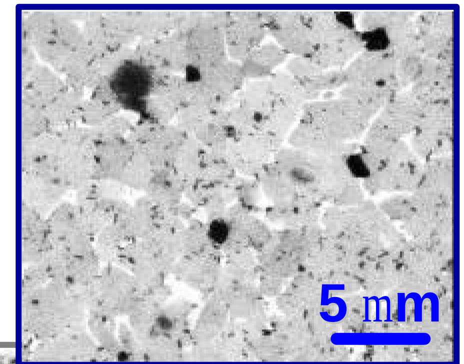


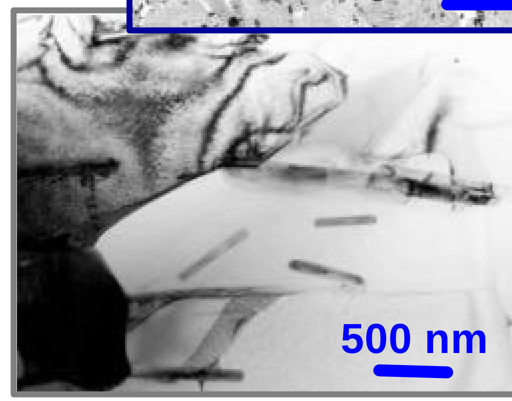
	Ti-6Al-4V	Ti-6Al-4V-0.5B (3% TiB)	Ti-6Al-4Sn-4Zr-1Nb-1Mo-0.2Si-0.8B (5% TiB)	Ti-6Al-4V-1.6B *(3D)* (10% TiB)	Ti-6Al-4V-3.0B *(1D)* (20% TiB)	GOAL
Modulus (GPa)	110-115	125	132	136	200	2X matrix
YS (MPa)	840-1070	1007	1175	1400	1250	1.5X matrix
UTS (MPa)	940-1180			1500	1350	1.5X matrix
Strain (%)	7-20%	9.5	5.0	2.4	2.6	>5%
K_{IC} (MPa.Öm)	44--110	47		40-55		>50
Fat Str (MPa) (>10^6 cyc)	494-744		675			>1000
T_{max}	427°C/800°F					600°C/1100°F

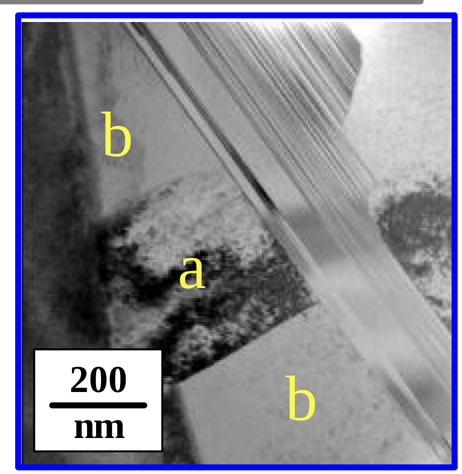
Ti-B ALLOYS

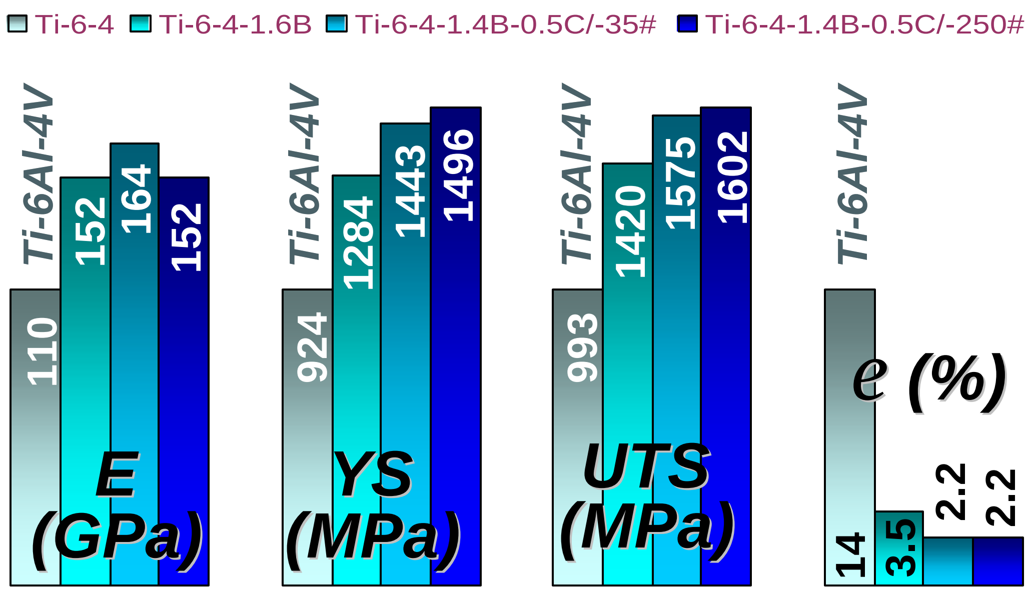
A new class of Ti alloys provides dramatic increases in structural properties

- TiB whiskers are thermodynamically stable
  - ❖ micron-sized whiskers are ~1μm diameter with *l/d* ~ 10:1
  - ❖ submicron whiskers are ~100nm diameter with *l/d* ~ 10:1
- TiB provides strength and stiffness
  - ❖ uniform dispersion of TiB achieved *in situ*
  - ❖ alignment of TiB easily achieved via extrusion, rolling
- P/M is currently being studied; casting offers large payoff in performance and affordability









SUMMARY

Ti-B alloys offer exceptional promise for development and transition into aerospace systems

- exceptional structural properties for enabling defense applications
  - increases in strength and stiffness of ~50% already achieved
- microstructure and properties tailorable over a very wide range
- cast, wrought, P/M and advanced processes are feasible
- affordability comparable to conventional Ti products

Different primary process paths provide three materials with distinct characteristics

- as-cast product for lowest cost, especially in complex shapes
- pre-alloyed P/M for best balance of structural efficiency and affordability
- blended elemental P/M product for highest structural efficiency

Approaches underway to address technology challenges

- elimination of primary TiB
- optimization of primary and secondary process parameters
- characterization of 1^{st} and 2^{nd} tier properties
- technology issues of joining and machinability

OUTLINE

- HIGH STRUCTURAL EFFICIENCY
- STRUCTURAL EFFICIENCY OF METALLIC MATERIALS
- **CANDIDATE TECHNOLOGIES**
  - MMCs
  - Advanced Al
  - Ti-B Alloys
  - **Metallic Glasses**
- SUMMARY

AMORPHOUS METALS
Introduction

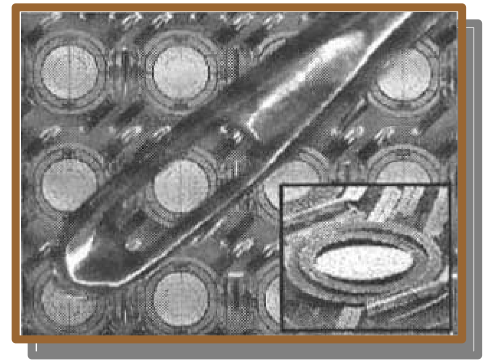
What are amorphous metals?
- ❖ no long range atomic symmetry or periodicity

How are they produced?
- ❖ usually by rapid quenching
- ❖ in a few alloys, rapid quenching is not needed

What makes them 'special'?
- ❖ exceptional structural, magnetic, corrosion properties
  - ✓ *strengths up to 2% of the elastic modulus are achieved (up to 3 GPa)*
- ❖ plastic-like manufacturing (injection molding)
- ❖ may possess exceptional damping properties

What are the technical challenges?
- ❖ lack of symmetry eliminates experimental techniques for characterization of structure
- ❖ fundamental mechanisms of strengthening, deformation, mass transport, etc. are not known
- ❖ what controls stability?

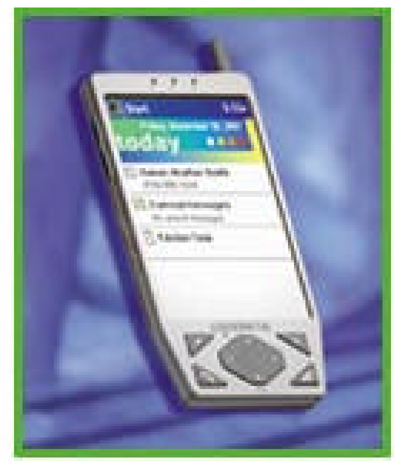
AMORPHOUS METALS
Current Applications

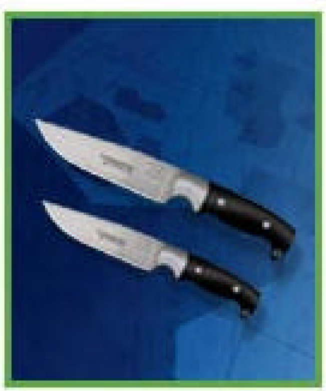


Low loss magnetic material
- ❖power transformers
- ❖magnetic resonance imaging (MRI) for medical field
- ❖video recording heads

Corrosion resistance
- ❖coatings for safety razors
- ❖coatings for nuclear containment currently being validated

Structural applications
- ❖golf club heads, tennis racquets, baseball bats
- ❖electronics cases for cell phones, laptops, PDAs
- ❖micro-mirror array hinges for digital projection systems





PLASTIC-LIKE PROCESSING OF AMORPHOUS METALS

Marginal glasses require rapid quench to form glass structure

- ❖ only very thin sections (<300mm) can be formed

Thicker sections (>1cm) can be formed in bulk glasses

- ❖ process time increases dramatically after cooling below the ‘nose’
- ❖ provides opportunity for metal injection molding

Metal injection molding is now being used for a wide range of consumer goods

- ❖ metals compete successfully with plastics for both cost and performance
- ❖ electronics, sports, jewelry applications
- ❖ provides approach for unitized construction of complex shapes where volume is an important consideration

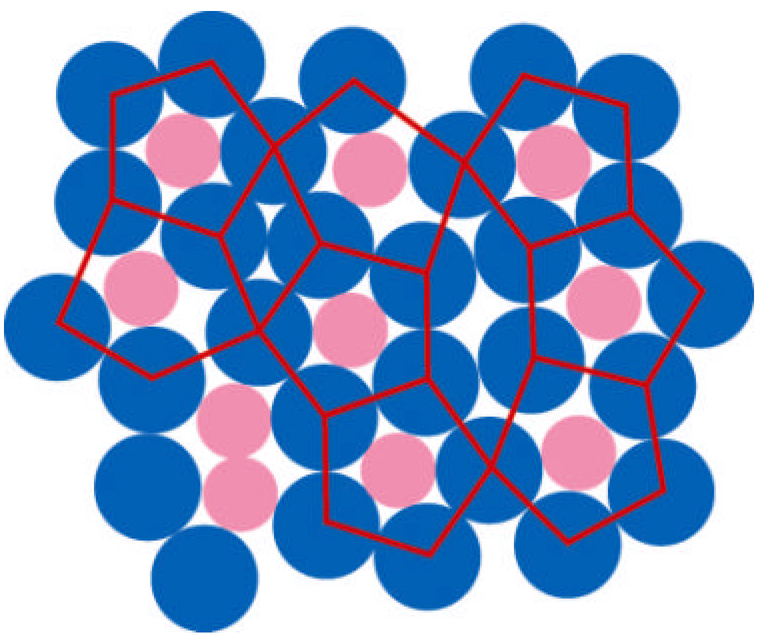
SAMSUNG CELL PHONE CASE

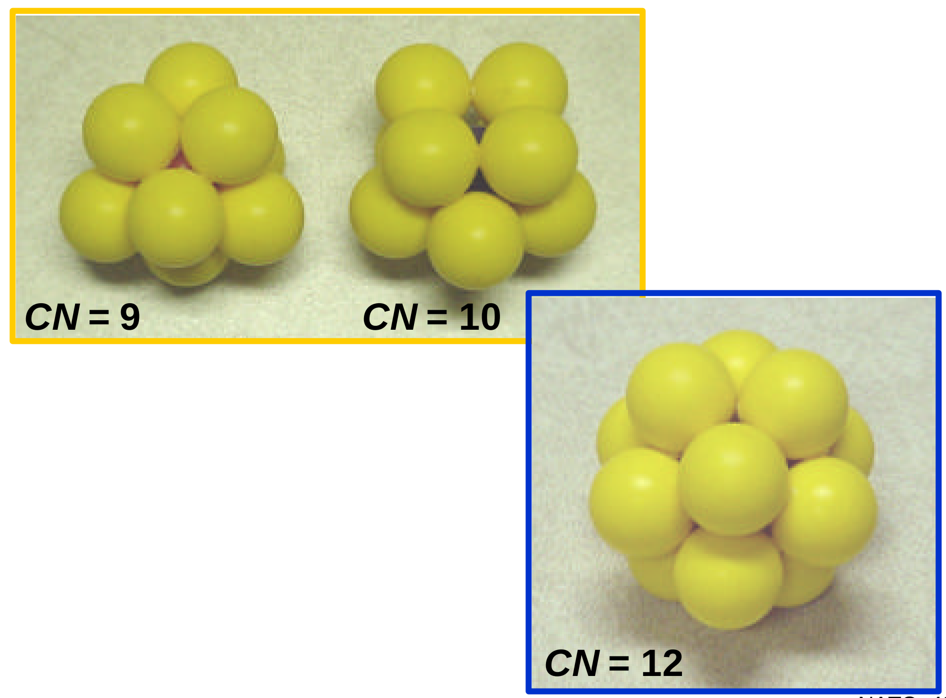
AMORPHOUS METALS (a-METALS) STRUCTURE

Stability, strength, deformation and properties are all tied to the atomic structure

IH research is developing a structural model to guide exploration of new BMGs and exploitation of a-metals

Atomic clusters about 3 atom diameters (<1nm) are the fundamental building blocks of the atomic structure



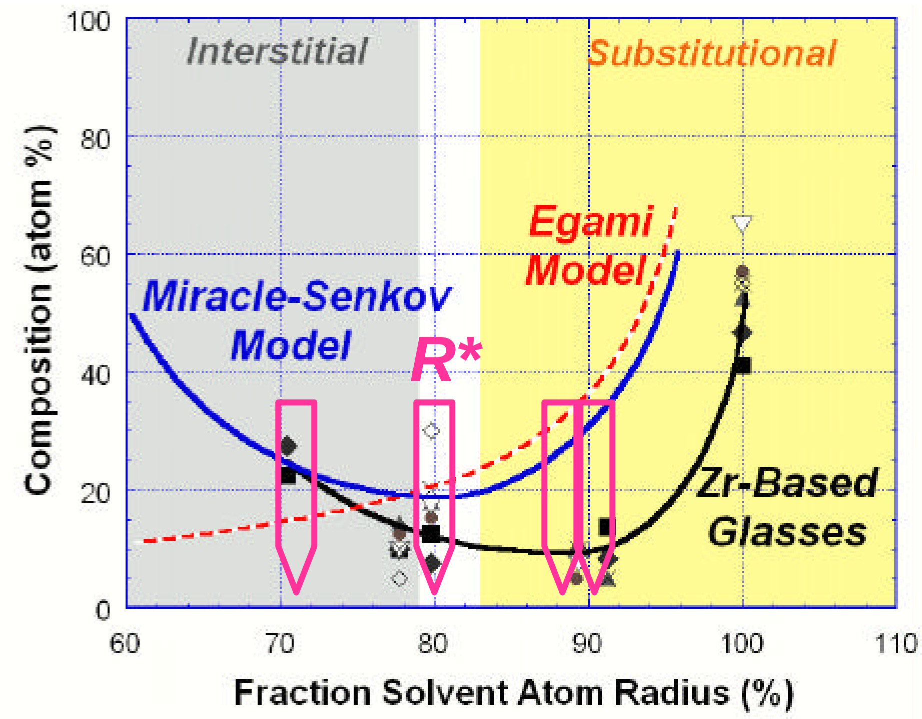


PRINCIPLES OF METALLIC GLASS FORMATION

Our research has established:

- a phenomenologically-based characteristic topology for BMGs that shows a clear relationship between atom size and concentration
  - previous topological models could not reproduce the observed trends
- a physically-based model that reproduces the observed topological trends
  - based on substitutional or interstitial solute occupancy in the competing crystalline lattice depending on solute radius ratio, *R*
- a model based on the structure-forming principle of efficient atomic packing that predicts that solutes with specific sizes relative to the solvent atoms (*R**) are preferred in BMGs

Together, these models provide specific guidance for the exploration of new BMGs



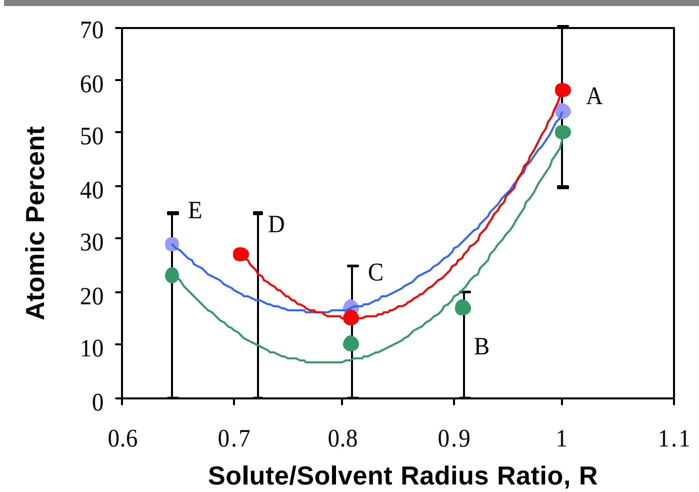
EXPLORATION OF NEW BMGs
Results

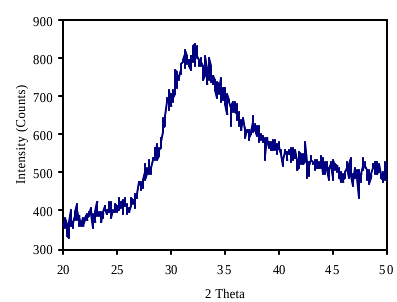
Two new BMG systems have resulted from this research

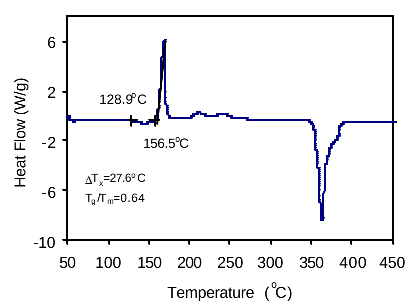
- ✓Fe-based BMG developed at INEEL as part of DARPA SAM Initiative
- ✓Several Ca-based glasses discovered in-house at ML
  - ➢***12 of 15 alloys are fully amorphous in 1 mm cast plate***

Discovery of new BMGs is necessary to take full advantage of plastic-like processiblity

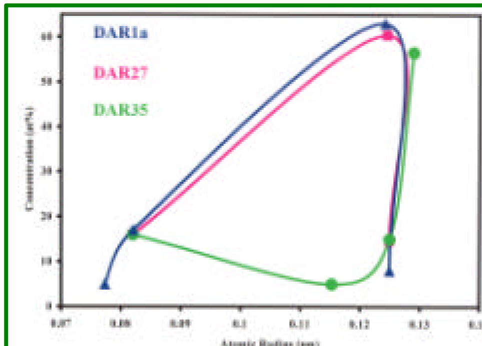
$Ca_A(Y,Ln)_B(Mg,Sn)_C(Zn,Al,Ag)_D(Cu,Ni,Si)_E$

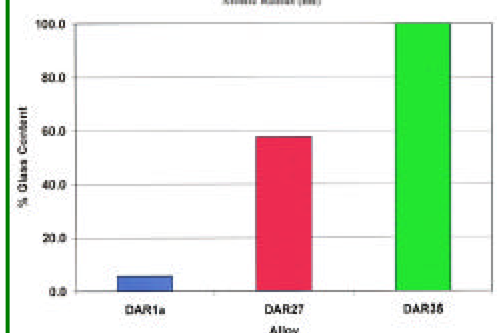






O.N. Senkov, UES, Inc.





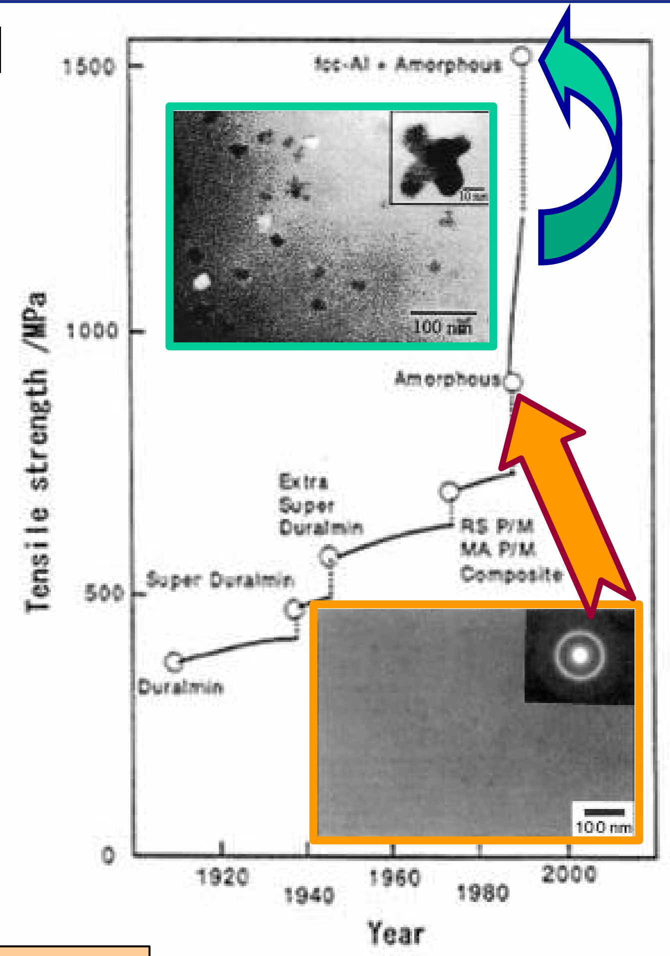
Courtesy D. Branagan

In Situ NANOCRYSTALS IN AMORPHOUS METALS

Nanocrystal dispersions can be formed *in situ* in amorphous Al
- ❖ Al nanocrystals are 5-10 nm in diameter
- ❖ Al nanocrystals occur at an exceptionally high number density (10^{21} to 10^{23} /m^3)

Improves both strength and ductility
- ❖ mechanisms of improvements unknown

Mechanism of nucleation unknown
- ❖ conventional mechanisms (homogeneous and heterogeneous nucleation) do not fit experimental observations



Control of nanocrystalline precipitation represents the next challenge to control properties of amorphous Al

A. Inoue, H. Kimura; *Mat. Sci. Eng.*, 2000

TECHNOLOGY ISSUES

How to make bulk glasses?

– required to produce bulk components
  - restricted thermal stability makes consolidation and forming of marginal glasses a significant technical challenge
  - enables ‘plastic-like processing’ below the nose of the TTT curve

A scientific basis is being established and applied to produce new bulk metallic glass systems for wider commercial applications

How to provide fracture properties (ductility, toughness)?

– two-phase co-continuous crystalline/amorphous microstructures

– nanocrystalline dispersion via controlled precipitation

Approaches have been conceived and validated for amorphous/crystalline composites, but much more work is required to understand and control devitrification process to produce nanocrystalline dispersions

OUTLINE

HIGH STRUCTURAL EFFICIENCY

STRUCTURAL EFFICIENCY OF METALLIC MATERIALS

CANDIDATE TECHNOLOGIES

APPLICATIONS

SUMMARY

SUMMARY

DoD emphasis on high temperature materials now being joined by requirements for high specific strength, stiffness

- enables structural minimization for highly efficient structural designs
- configuration of future systems will be controlled by these properties
- strong impact on systems affordability

A broad range of AF systems require materials with exceptional specific strength and stiffness

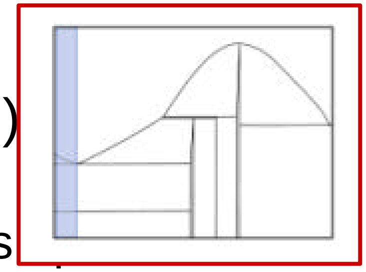
- space systems
- current and future aeronautical systems
- sustainability of existing fleet

Affordable metallic materials approaches for achieving exceptional specific properties are being pursued

- metal matrix composites (discontinuous and continuous reinforcements and ‘hybrid’ composites)
- advanced Al alloys
- boron-modified Ti alloys (Ti-B)
- amorphous and nanocrystalline metals

QUESTIONS?

CAST Ti-B ALLOYS
“Composition and Processing”



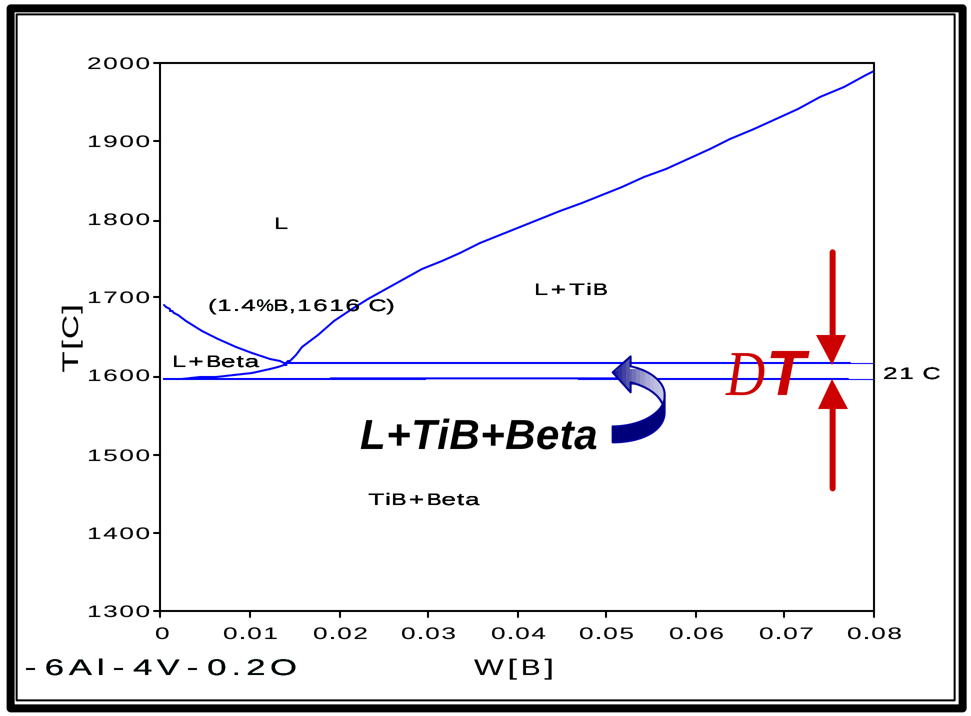
Limited casting experience

- ingots have been cast using induction skull melting (Duriron) and consumable electrode (Timet)
  - skull melt billets up to 4” diameter, consumable electrode billets to 14” diameter
- boron addition is fully dissolved in molten alloy
- compositions limited to eutectic and hypoeutectic alloys

Cost comparable to conventional cast product is expected

Casting studies required

- elimination of primary borides
- O increases ΔT, C slightly reduces ΔT, Sn and Zr significantly reduce ΔT

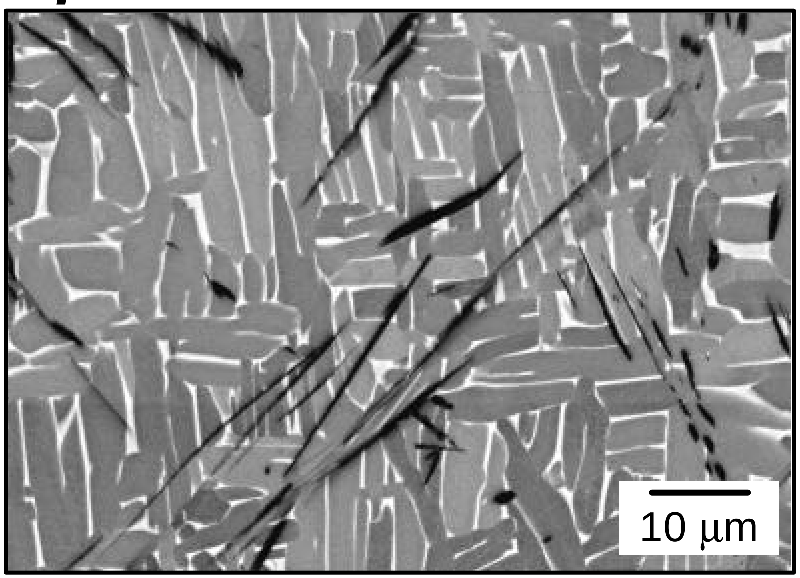


CAST Ti-B ALLOYS
"Microstructures and Properties"

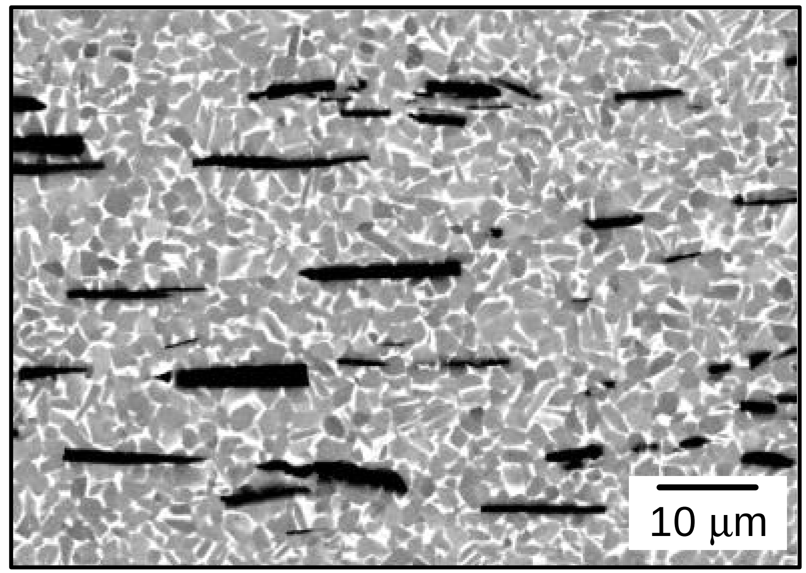
Boron additions exert important influence on microstructures

- primary borides and micron-sized borides are produced, but no submicron TiB
- uniform boride distribution and random orientation produced
- borides stabilize fine grain size

Properties of as-cast Ti-B alloys not available



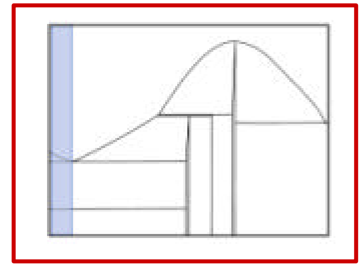
Cast + HIP



After Extrusion

Cast material courtesy PCC Structurals, Albany OR

PREALLOYED POWDER
“Composition and Processing”

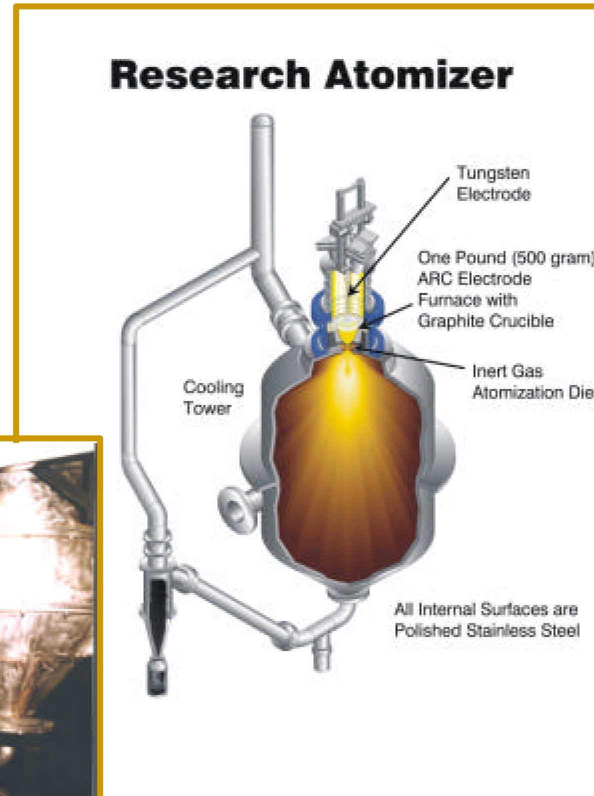


Use conventional powder production

- compositions limited to eutectic and hypoeutectic alloys
- boron addition is fully dissolved in molten alloy
- molten alloy is converted to powder via inert gas atomization at Crucible Research

Use conventional powder consolidation

- vacuum degas at RT/24h + 300C/24h with argon backfill between steps
- blind die compaction at 1400MPa/1200C/180s
- extrusion at 1100C / 16:1 / 6mm/s



Cost comparable to conventional P/M product is expected

PREALLOYED POWDER
“Microstructures”

Uniform distribution, random orientation of TiB formed in as-produced powder

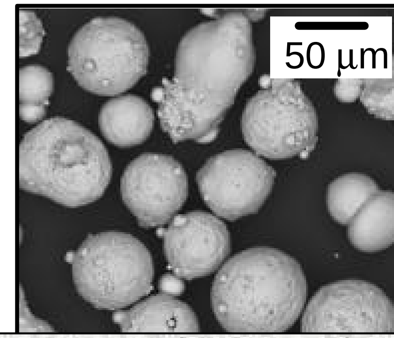
Eutectic composition (~1.6 wt% B) limits TiB volume fraction to ~10%

***Powder consolidation produces* microstructural changes**

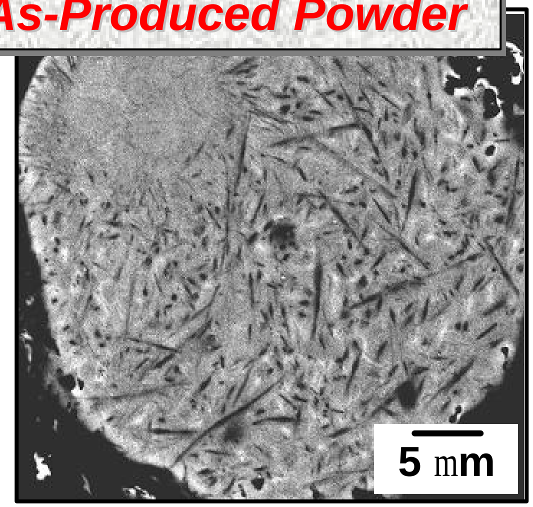
– fine grained α/β microstructure with coarsening of TiB

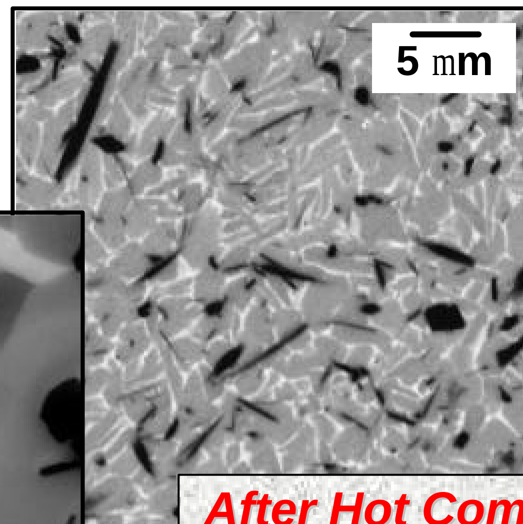
Nanometer-sized TiB is unique feature of P/M Ti-B alloys

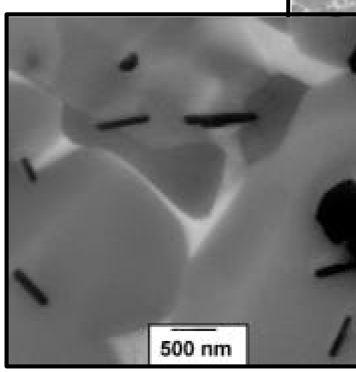
– retained after consolidation



As-Produced Powder



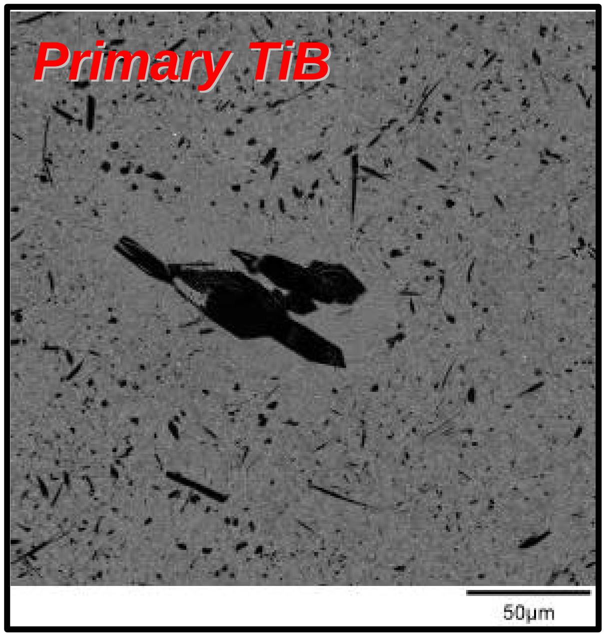


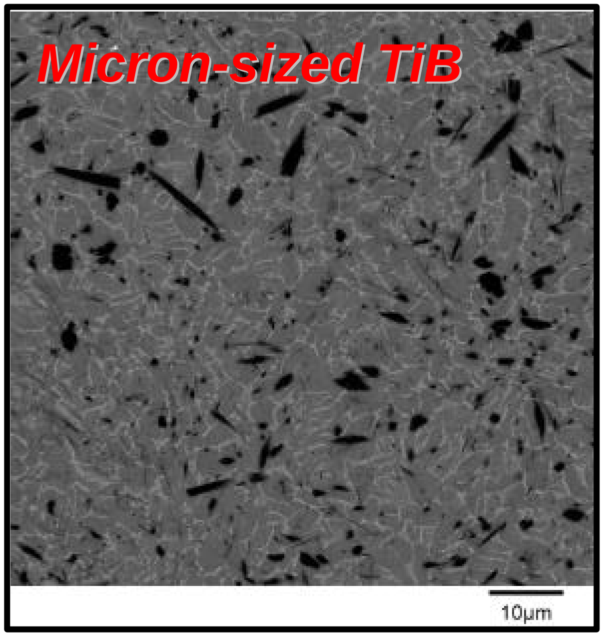


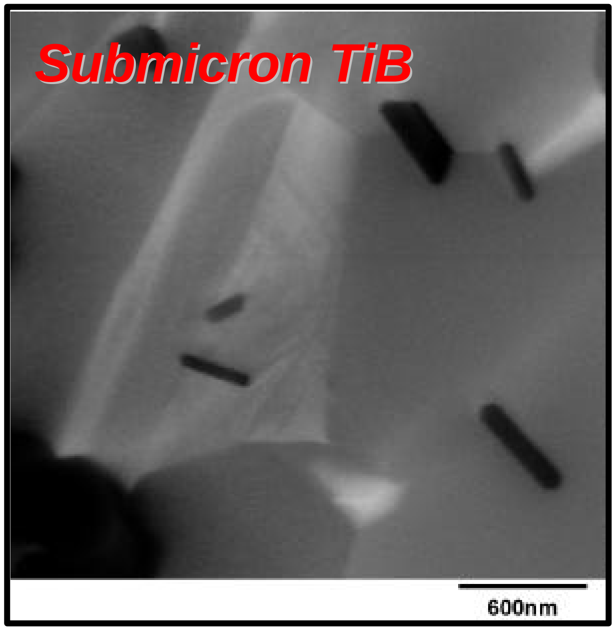
After Hot Compaction

PREALLOYED POWDER
"Microstructures"

TiB is produced in a range of sizes

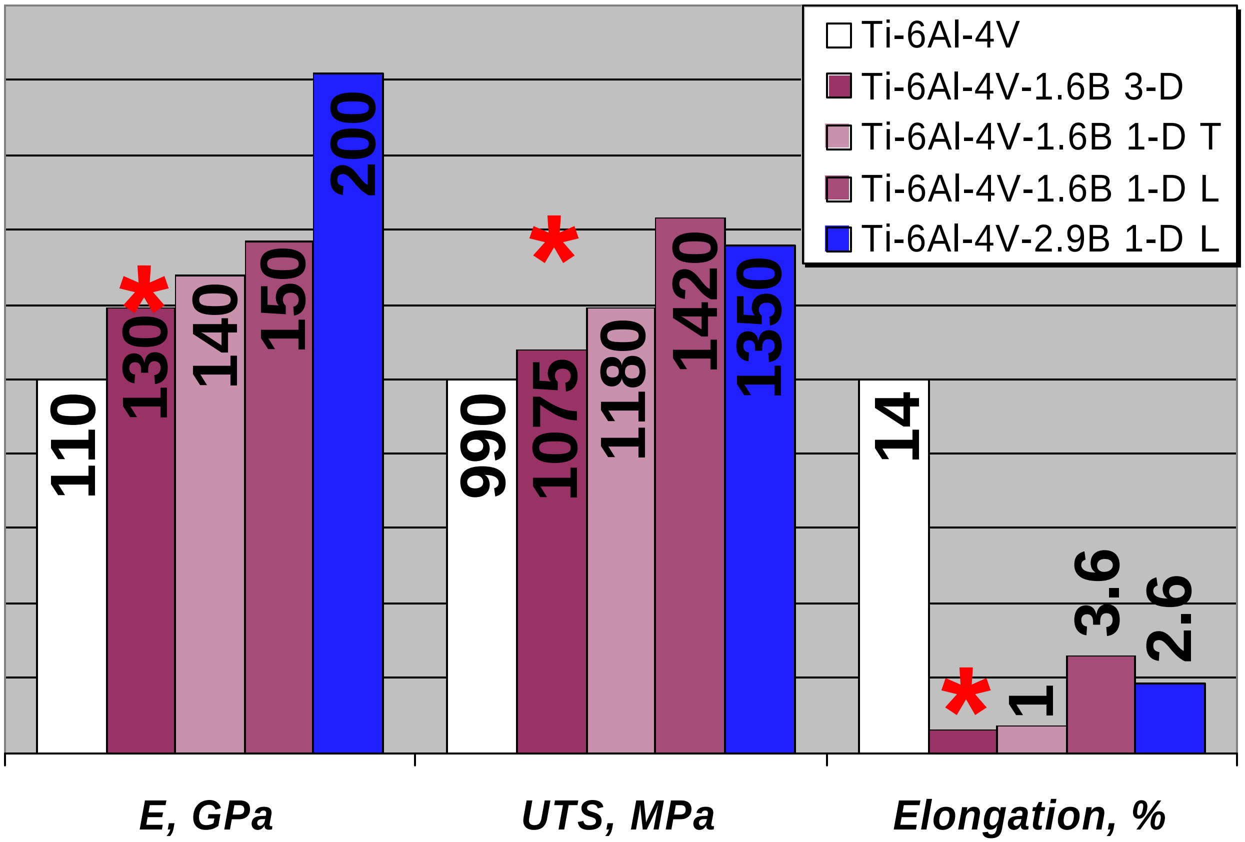






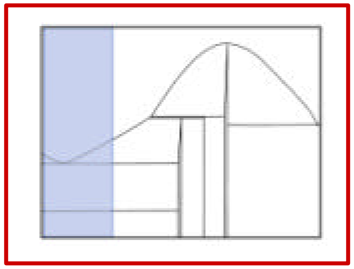
Ti-6Al-4V-1.6B billet from -100# (<150mm) Powder
Blind Die Compacted @1200°C/1400 MPa AC

PREALLOYED POWDER
“Properties”



- ✓ **Stiffness -80% and strength -40% compared to Ti-6Al-4V**
- ✓ **Strength increases maintained at elevated temperatures**
- ✓ **Improved properties by thermo-mechanical processing (*)**
- ✓ **Fracture toughness values in the range 40-55 MPaÖm**

BLENDED ELEMENTAL POWDER "Compositions and Processing"



Compositions expanded to include hypereutectic

- solid state processing eliminates primary borides
- desired compositions achieved by blending elemental metal powders or master alloy powder with B or TiB_2 powder

Blend + outgas + consolidate + react

- powder blending (wet /24 hr + dry/0.5 hr)
- degas and seal (RT/24 hr + 300°C/24 hr)
- blind die compact (1200°C/1400 MPa/180 sec)
- heat treat to transform B or TiB_2 to TiB (1300°C/6 hr)

Process path is similar to that for conventional discontinuously reinforced metals

- additional step to fully react TiB_2 to form TiB

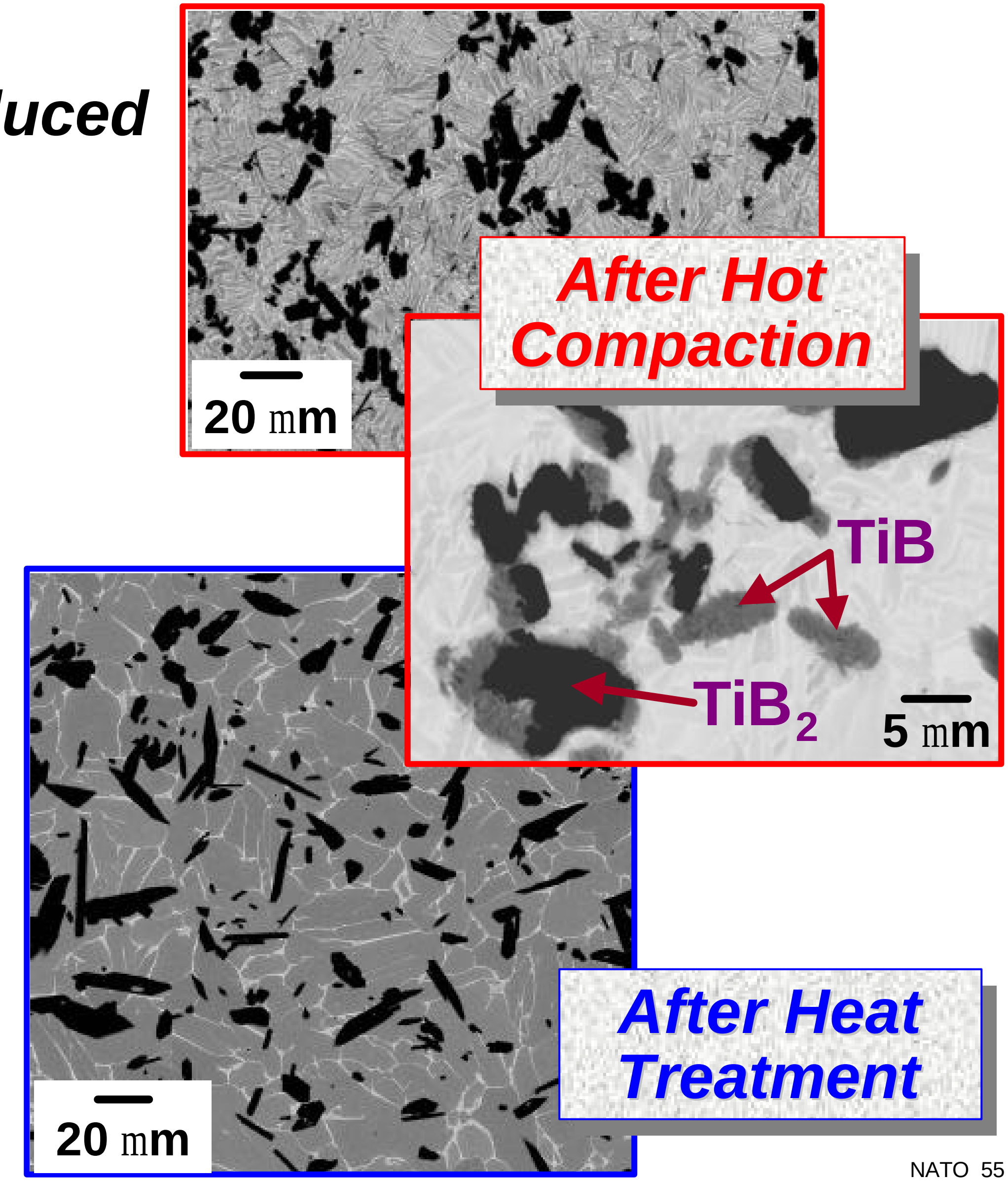
BLENDED ELEMENTAL POWDER
“Microstructure and Properties”

Uniform distribution of randomly oriented TiB produced

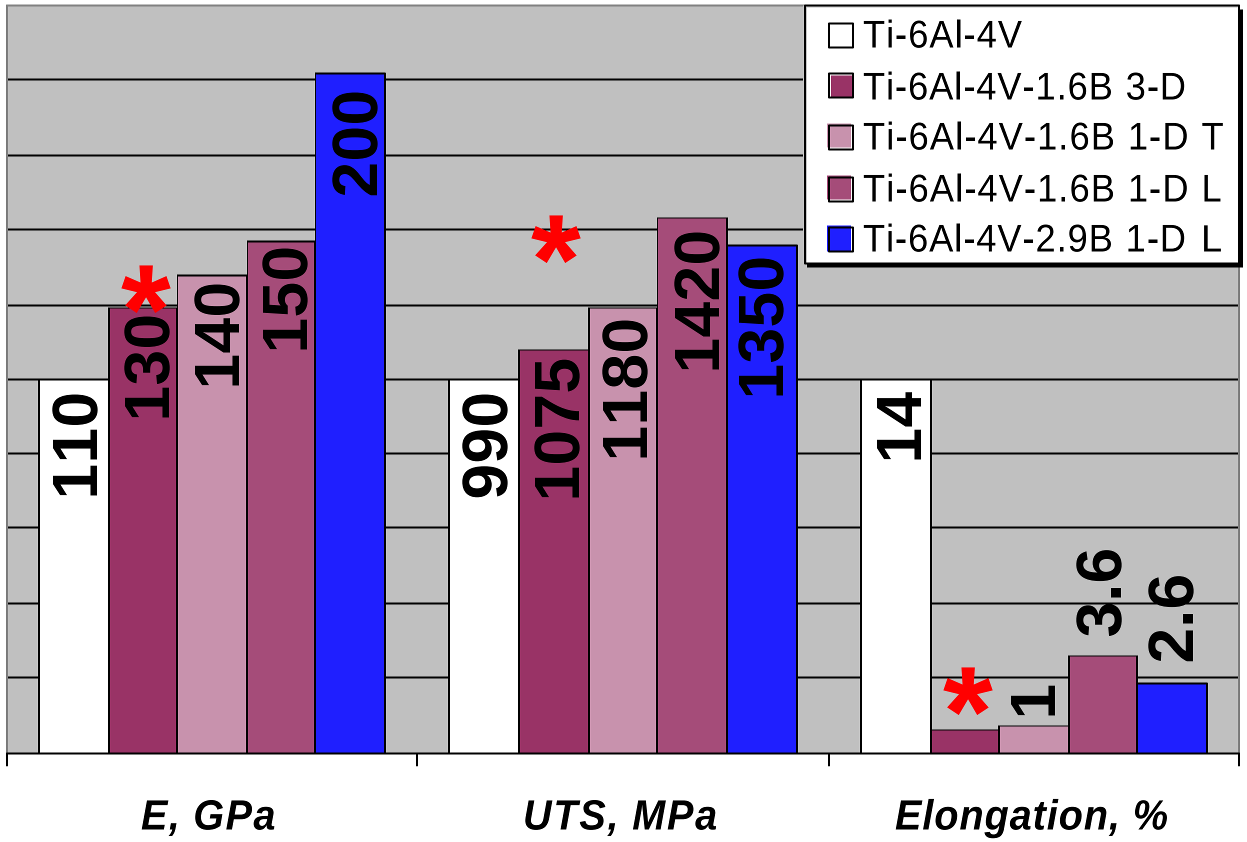
- primary and submicron TiB eliminated
- fine alloy grain size is retained
- effective blending required to eliminate TiB clustering

BE offers possibility of higher specific properties via hypereutectic concentrations

- BE product will not compete with PA at equivalent B content
- isotropy/ anisotropy can be tailored by subsequent thermo-mechanical processing



BLENDED ELEMENTAL POWDER
"Properties"



- ✓ **Higher stiffness relative to alloys with lower B content**
- ✓ **Slightly lower strength- currently limited by inadequate processing**
- ✓ **Additional characterization required**

OBJECTIVE

Double the structural efficiency of conventional Ti alloys at comparable cost

- enabling specific stiffness *and* specific strength (2X compared to existing aerospace structural metals) and useful fracture properties
- full-life elevated temperature capabilities extended by 150°C compared to conventional Ti matrix alloys
- establish primary and secondary processing techniques (including casting) capable of producing useful product forms
- produce and validate selected components for defense applications

IMPLEMENTATION STRATEGY

Identify cross-industry opportunities and teams

- multiple markets provide larger motivation for materials suppliers
- provides pervasive market impact
- spreads risk and cost of development, certification, insertion
- lack of direct competition encourages open cooperation

Form technology teams

- an internal advocate at each partner organization is essential
- interaction between design and material is a required activity

Include all stakeholders

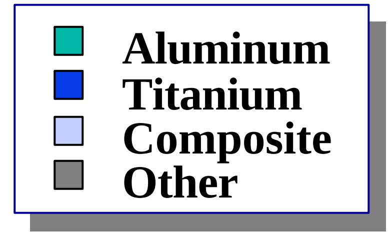
- early enough to impact system requirements
- strong contribution from materials suppliers
- academia, industry and national / government labs

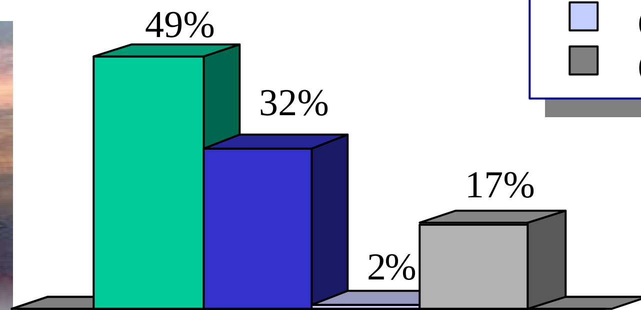
Demo programs are essential

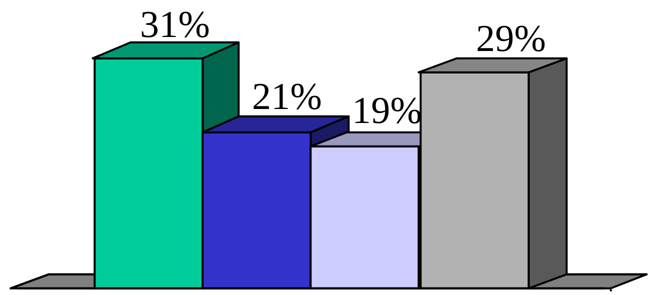
- provides direct and immediate path for material validation
- provides imperative for material / design interactions

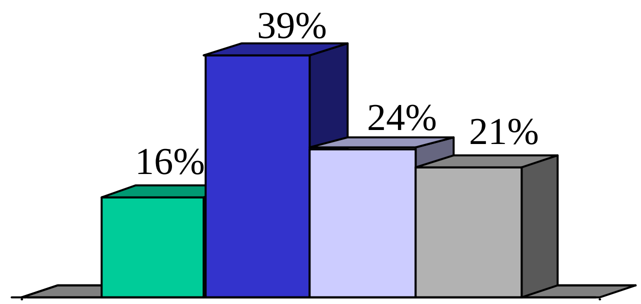
Fighter Aircraft Materials

Utilization Of High Cost Airframe Materials Has Been Increasing To Improve Aircraft Performance









Affordability Is Now Being Emphasized When Selecting Airframe Materials

Ti-B APPLICATIONS

Potential applications for Ti-B technology include any where higher structural efficiency will produce significant improvement in performance, capability or affordability

***Cast Ti-B* for improved properties at lowest cost and/or complex shapes**

***Prealloyed Ti-B* for significant improvement in structural efficiency at cost of typical Ti P/M product**

***Hybrid materials* provide an opportunity to expand capabilities of continuously reinforced Ti MMCs**

– incorporate Ti-B alloys as matrices in TMCs

***Blended elemental Ti-B* may produce highest structural efficiency at a premium in cost**

– **cost increment comparable to that of conventional discontinuously reinforced MMC**

NUCLEATION CONTROL IN AMORPHOUS METALS

Solute distribution plays a critical role in nanocrystal nucleation

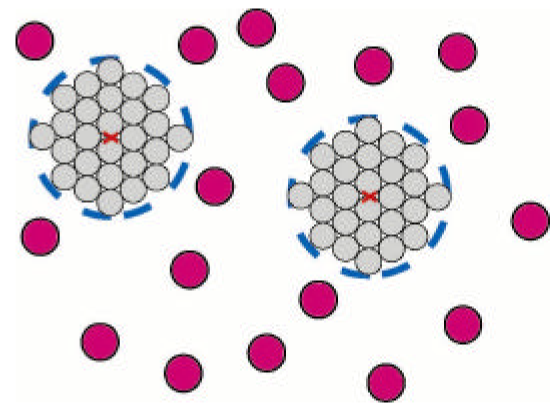
- ❖ solute-free regions allow nanocrystals to form

Atomic simulation of solute distribution shows good agreement with experiment

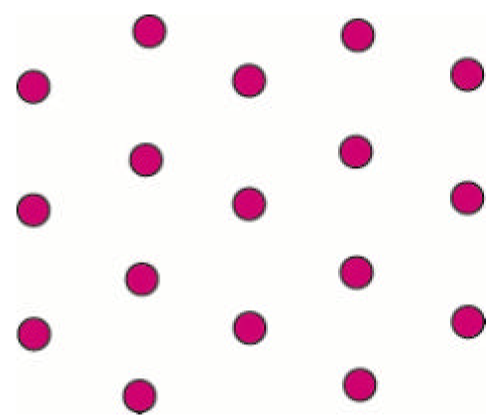
Solute distribution is manipulated through solute-solvent chemical bonding

- ❖ controls chemical short range ordering

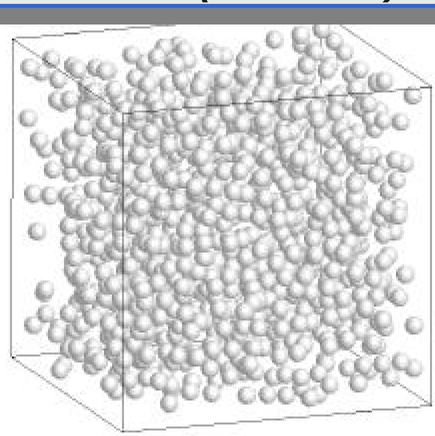
RANDOM SOLUTE ATOM ARRAY

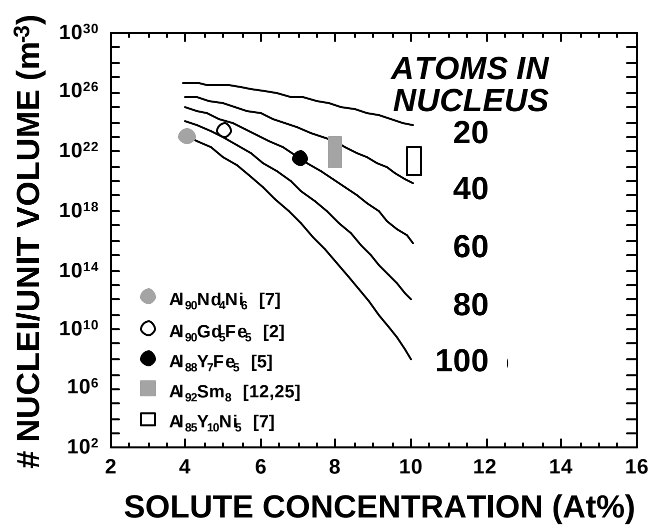


REGULAR SOLUTE ATOM ARRAY



RANDOM SOLUTE ATOM ARRAY (10^7 atoms)





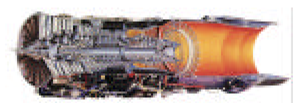
POTENTIAL APPLICATIONS
"Materials with High Structural Efficiency"

AEROSTRUCTURES

- elevated temperature DRA, amorphous Al to replace Ti at 150–200°C
- metallic materials with high specific strength/stiffness to replace gr/epoxy sheet
- affordable unitized construction for conventional and revolutionary (UAV) aircraft

AEROPROPULSION

- replace Ti in compressor for existing and future (JSF) systems
  - ✓ LPC blades and stators, HPC stators and shrouds, fan blades (long term)
  - ✓ flow path sheet structures, bleed valves, shrouds and bearing supports



- reduced mass and cost for rings, cases

SPACE

- isotropic material with high specific strength is principle requirement for cryo turbopumps and propellant management devices

  - ✓ housings, inducers, impellers, lines, ducts, flanges, structural jacket
- many applications for orbital systems
  - ✓ bus structures, truss nodes, brackets, hinges, radiator panels, PCB heat sinks . . .

SUSTAINMENT

- direct substitution for overspecified materials to maintain form/fit/function
  - ✓ higher specific properties can support loads unanticipated in original design
  - ✓ examples include F-16 ventral fin, B-1 bungee wedge link, F-15 door skin . . .
- amorphous Al offers possibility of dramatically reduced corrosion